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APRITES EKONOMIKAS LĒMUMU PIEŅEMŠANAS ALGORITMS

Promocijas darbs

RĪGAS TEHNISKĀ UNIVERSITĀTE

Dabaszinātņu un tehnoloģiju fakultāte
Vides aizsardzības un siltuma sistēmu institūts

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Doktora studiju programmas "Vides inženierija"

APRITES EKONOMIKAS LĒMUMU PIEŅEMŠANAS ALGORITMS

Promocijas darbs

Zinātniskās vadītājas

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ANOTĀCIJA

Šā brīža aktualitāte ir ilgtspējas jautājumi, atkritumu apsaimniekošana, klimatneitralitāte un kopumā Eiropas Savienības nospraustais Zaļais kurss. Šie ir sarežģīti jautājumi –izaicinājumi, kas sastāv no ļoti daudzām niansēm. Šos izaicinājums pamatā risinās nākotnes tehnoloģijas, no kurām daudzas ir vēl tikai iedīglī. Tomēr tehnoloģijas ir ne tikai jārada, bet arī jēgpilni jāizmanto, jākombinē un jāoptimizē. Ir jābūt skaidrai izpratnei, ar kādu izejvielu, atkritumu, blakusproduktu vai atlikumu strādāt kā ar resursu, vai jebkurš atlikums ir izmantojams kā resurss, kāds ir optimāls tehnoloģiskais process, kādi aspekti jāvērtē analizējot. Tātad katrs potenciāli izmantojamais resurss, katra tehnoloģiskā vienība un katrs plānotais produkts ir rūpīgi jāvērtē caur resursu patēriņa, ražošanas, resursu aprites potenciāla, ietekmes uz klimata pārmaiņām, atkritumu apsaimniekošanas, enerģijas pārvaldības un ekonomisko aspektu prizmu, lai rezultātā iegūtajam produktam būtu maksimāli augsta pievienotā vērtība. Tāds arī ir šī promocijas darba vadmotīvs: septiņreiz nomēri, pirms griez jeb investē!

Darba mērķis ir izpētīt, kādas metodes ir lietojamas un kā tās ir kombinējamas, lai ražošanas procesa atlikumus vai produktus, kas ir sava dzīves cikla noslēgumā, izmantotu kā resursus jauna, augstākas pievienotās vērtības produkta ražošanā.

Promocijas darbs ir veidots kā publikāciju kopa, kas sastāv no astoņām tematiski vienotām zinātniskajām publikācijām, kas sarakstītas doktorantūras studiju laikā. Tās ir publicētas žurnālos ar augstu ietekmes faktoru (kvartelēs Q1 un Q2) un indeksētas starptautiskajā datubāzē *SCOPUS*.

Promocijas darbs sastāv no ievada, četrām nodaļām un pielikumā apkopotām visām astoņām oriģinālajām publikācijām angļu valodā. Ievaddaļā aplūkota tēmas aktualitāte, hipotēze, mērķi un uzdevumi, darba struktūra un informācija par darba aprobāciju. Promocijas darba četras nodaļas sastāv no literatūras analīzes, metodoloģijas, pētījumu rezultātiem un diskusiju daļas. Darba noslēgumā ir apkopoti būtiskākie secinājumi par izstrādāto promocijas darbu un sniegtas rekomendācijas par turmākajiem nepieciešamajiem soļiem aprites ekonomikas attīstībai.

ANNOTATION

Sustainability issues, waste management, climate neutrality and the overall "Green Deal" path set by the European Union are topical at the moment. These are complex issues, rather challenges, which are made up of a great many nuances. Future technologies, many of which are still in their infancy, will be at the heart of these challenges. But technologies need not only to be created, but also to be used, combined, optimised and rationalised. There must be a clear understanding of what raw material, waste, by-product or residue to work with as a resource. And is any residue usable as a resource? What is the optimal technological process to design? What aspects to analyse? So every potentially usable resource, every technological unit and every planned product must be carefully analysed through the prism of resource consumption, production, resource cycling potential, climate change impacts, waste management, energy management and economics in order to produce a product with the highest possible added value. This is the guiding principle of this thesis, measure seven times before you cut or invest!

The aim of the work is to investigate which methods can be applied and how they can be combined to use residues or products at the end of their life cycle as a resource to produce a new product with the highest possible added value.

The thesis is a collection of eight thematically coherent scientific publications written during the doctoral studies. They have been published in high impact factor journals, quartiles Q1 and Q2, and indexed in the international database SCOPUS.

The thesis consists of an introduction, four parts and an appendix summarising all eight original publications in English. The introductory part contains the topicality of the topic, the hypothesis, the aims and objectives, the structure of the thesis and information on the validation of the thesis. The four parts of the thesis consist of a literature review, methodology, research results and discussion. The thesis concludes with a summary of the main conclusions of the thesis and recommendations on the most immediate steps needed for the development of the circular economy.

SATURS

SAĪSINĀJUMI

SEG – siltumnīcefekta gāzes

ES – Eiropas Savienība

MCDA – daudzkritēriju lēmumu pieņemšanas metode

ACN – aprites cikla novērtējums

COVID-19 – koronavīrusa slimība

CO/PES – kokvilnas un poliestera kombinācija

OSB – orientēto skaidu plātne

PB – skaidu plātne

MDF – vidēja blīvuma kokskaidu plātne

IPCC – Klimata pārmaiņu starpvaldību padome

LPTP – labākais pieejamais tehniskais paņēmiens

CLT – šķērsām līmēta koksne

reCLT – otrreizēji pārstrādāta *CLT*

EoL – pēc kalpošanas laika beigām

CBM – aprites uzņēmējdarbības modeļi

MKF – melamīn-karbamīda formaldehīds

PUR – poliuretāns

FCM – izplūdušo kognitīvo karšu modelēšanas metode

BHET – bis(2-hidroksietil)tereftalāts (monomērs jeb starpprodukts, kas rodas, pārstrādājot PET plastmasu)

IEVADS

Eiropas Savienība (ES) ir noteikusi skaidru kursu uz ilgtspējīgu attīstību, uzsverot nepieciešamību pāriet no lineārās ekonomikas uz aprites ekonomikas modeli. Tradicionālā pieeja – "paņem–izmanto–izmet" vairs nav uzskatāma par dzīvotspējīgu risinājumu mūsdienu resursu patēriņa un vides slodzes kontekstā. Aprites ekonomika piedāvā alternatīvu, kuras centrā ir esošo materiālu un produktu dzīves cikla pagarināšana, atkārtoti tos izmantojot, remontējot, pārstrādājot un atgriežot tautsaimniecībā. Šāda pieeja ļauj būtiski samazināt atkritumu daudzumu un veicina resursu efektivitāti visā ekonomisko vērtību ķēdē.

Statistikas dati liecina, ka ES ik gadu rodas vairāk nekā 2,2 miljardi tonnu atkritumu, no kuriem ievērojama daļa joprojām tiek apglabāta poligonos. Vienlaikus rūpnieciskie procesi un produktu lietošana veido 9,1 %, bet atkritumu apsaimniekošana – 3,32 % no kopējām siltumnīcefekta gāzu (SEG) emisijām ES līmenī. Jau produkta izstrādes stadijā tiek noteikts līdz pat 80 % no tā kopējās ietekmes uz vidi. Tas nozīmē, ka ilgtspējīgai ražošanai ir jābalstās stratēģiskajā plānošanā jau agrīnā posmā. Šo apsvērumu dēļ Eiropas Parlaments 2021. gada februārī pieņēma rezolūciju par jauno aprites ekonomikas rīcības plānu, nosakot ambiciozus mērķus oglekļneitralitātes sasniegšanai līdz 2050. gadam, kā arī saistošus kritērijus attiecībā uz materiālu izmantošanu līdz 2030. gadam [177].

ES politikas dokumentos īpaša uzmanība pievērsta nozarēm ar augstu resursu patēriņu un būtisku ietekmi uz vidi. Viena no šādām jomām ir tekstilrūpniecība, kas 2022. gada martā kļuva par mērķi īpašai ilgtspējas, inovāciju un pārstrādājamības veicināšanas stratēģijai. ES tekstilizstrādājumu produktu grupu ir noteikusi kā vienu no septiņām galvenajām produktu vērtību ķēdēm, kurām pāreja uz aprites ekonomiku tiks piešķirta prioritāte [7]. Tas apliecina, ka aprites ekonomikas ieviešana nav vien teorētiska koncepcija, bet gan praktiska nepieciešamība un politiski atbalstīts virziens.

Vienlaikus, neskatoties uz skaidri definētiem mērķiem un rīcības virzieniem, praksē joprojām pastāv būtiski izaicinājumi: kā izvērtēt iespējamos ieguvumus, kādi rīki lietojami ilgtspējības analīzei un kādā aspektu struktūrā jāformulē investīciju lēmumi. Šāds strukturāls skatījums vienkopus ir fundamentāls aprites ekonomikas virzībai un ir šī promocijas darba pamatā.

Promocijas darba ietvaros ir veikta resursu (tekstila atlikumu, kokapstrādes atlikumu, pārtikas pārstrādes blakusproduktu, enerģijas atlikumu) analīze. Ir lietota daudzkritēriju analīze, aprites cikla novērtējums, bibliometriskā analīze, sistēmdinamika, izplūdušās kognitīvās kartes un CO_2 aprēķini, kā arī definēti un ņemti vērā izaicinājumi ceļā uz produktu ar augstāku pievienoto vērtību.

Darba aktualitāte

Eiropas Parlaments ir izstrādājis un noteicis par nepieciešamu pāreju no lineārā ekonomikas modeļa uz aprites ekonomikas modeli. Šī brīža aktualitāte ir maksimāli samazināt atkritumu apjomu, pagrināt produkta aprites ciklu, ideālā gadījumā – viena ražošanas procesa atkritumus padarīt par cita ražošanas procesa izejvielu vai resursu, tā atgriežot atpakaļ tautsaimniecībā. Rezolūcija par jauno aprites ekonomikas rīcības plānu paredz papildu pasākumus, lai līdz 2050. gadam panāktu oglekļneitrālu, ekoloģiski ilgtspējīgu, netoksisku aprites ekonomiku, tostarp stingrākus pārstrādes noteikumus un saistošus mērķus attiecībā uz materiālu izmantošanu un patēriņu līdz 2030. gadam [177], taču katrai dalībvalstij ir jārod savs visefektīvākais risinājums mērķu sasniegšanai dažādās tautsaimniecības jomās.

Darba mērķi un uzdevumi

Darba mērķis ir izpētīt, kādas metodes ir lietojamas un kā tās ir kombinējamas, lai ražošanas procesa atlikumus vai produktus, kas ir sava dzīves cikla noslēgumā, izmantotu kā resursus jauna, augstākas pievienotās vērtības produkta ražošanā. Jebkura resursu pārstrāde mazina ietekmi uz klimatu, nodrošina ceļu uz ilgtspējīgu attīstību un veicina produktu ar augstāku pievienoto vērtību attīstību.

Lai sasniegtu mērķi, tika izvirzīti trīs uzdevumi:

1) atlasīt resursus, kas ir ražošanas atlikumi vai produkti sava dzīves cikla noslēgumā, fokusējoties uz potenciālajiem resursiem, kuri ir pieejami lielā apjomā vai kuri lielos apmēros tiek noglabāti poligonos;

2) izvēlēties atbilstošas analīdzes metodes, definēt izaicinājumus ceļā uz produktu ar augstu pievienoto vērtību, radīt metožu kopumu vai kombināciju kā rīku sistēmu aprites ekonomikas attīstībai;

3) aprobēt metožu kopumu, izvērtējot dažādus ražošanas procesus, novērtēt iegūtos rezultātus un veikt pamatotus secinājumus.

Zinātniskā novitāte

Promocijas darba visaptverošais unikālais jaunievedums ir dažādu zinātnisko metožu izmantošana vienkopus, to secīga kombinēšana, lai attīstītu un paātrinātu virzību uz aprites ekonomiku ceļā uz produktu ar augstāku pievienoto vērtību. Tāpat metožu kopums izmantots ieviešanas soļu dinamiskai precizēšanai, identificējot visnozīmīgākos aspektus un definējot problēmu potenciālos risinājumus. Darbā ir izstrādāti jauni un saderīgi lietoto zinātnisko metožu atlases kritēriji. Katrā ražošanas procesā identificētas stiprās un vājās puses resursu patēriņa, energoefektivitātes, atkritumu mazināšanas un emisiju apjoma kontekstā.

Darba izstrādes gaitā vairākkārt un dažādās kombinācijās lietotas dzīves cikla novērtējuma un daudzkritēriju analīzes metodes. Izmantota sistēmdinamikas modelēšana, izplūdušā kognitīvā karte un SEG (CO_2) emisiju aprēķini. Dažādos griezumos ļoti plaši analizēta zinātniskā literatūra.

Šāda dinamiskā daudzlīmeņu un daudzdimensiju analīze kā strukturāls skatījums vienkopus ir kategoriski nepieciešama aprites ekonomikas virzībai un uzskatāma par promocijas darba centrālo zinātnisko novitāti.

Hipotēze

Aprites ekonomikai ceļā uz ilgtspējīgu attīstību viens no galvenajiem virzieniem ir produktu patēriņa samazinājums.

Praktiskā nozīme

Promocijas darbā paustās atziņas un secinājumi ir noderīgi Latvijai aprites ekonomikā, it īpaši tekstilatkritumu un koksnes izmantošanas jomā, politikas izstrādes un pilnveides procesā, ievērojot līdzšinējos atsevišķos centienus šajā sektorā Latvijā. Darba rezultāti ir svarīgi dažāda līmeņa institūcijām un tiem sabiedrības locekļiem, kuri iesaistās vai arī ir gatavi iesaistīties rūpniecības ražošanas blakusproduktu izmantošanā un jaunu uzņēmumu izveidē.

Tekstilatkritumu atkārtota izmantošana ir svarīga gan ministriju un valsts aģentūru ierēdņiem, gan pašvaldībām jaunu investoru piesaistei, gan arī jaunuzņēmumu investoriem.

Koksnes pilnvērtīgai izmantošanai piedāvātie risinājumi ir nozīmīgi meža un koksnes pārstrādes potenciālajiem investoriem.

Pārtikas ražošanas blakusproduktu plašais klāsts ir potenciālo investoru nākotnes izaicinājums. Promocijas darba zinātniskās izpētes piemērs šādā jomā varētu risināt un iedrošināt meklēt risinājumus šo blakusproduktu izmantošanai.

Enerģijas atlikumu izmantošana ir aktuāla visiem enerģijas lietotājiem.

Darba struktūra

Promocijas darba pamatā ir astoņu zinātnisko publikāciju kopa, kurās galvenā uzmanība ir pievērsta resursiem, kas ir cita ražošanas procesa atlikumi vai produkti, kas jau ir sava dzīves cikla noslēgumā, un to ceļu uz produktu ar augstāku pievienoto vērtību, izmantojot dažādas metodes, saskaroties ar problēmām un izaicinājumiem.

Promocijas darbā veikts literatūras apskats, kur izklāstītas diskusijas par potenciālajiem resursu veidiem, kuri sākotnēji ir šķiroti vai nešķiroti atkritumi, vai cita ražašanas procesa blakusprodukti, kā arī aplūkota līdz šim gūtā pieredze mērķu sasniegšanas akadēmiskajā analīzē.

Darbā izmantotas sešas pētniecības metodes:
1) daudzkritēriju lēmumu pieņemšanas metode;
2) izplūdušās kognitīvās kartes;
3) sistēmdinamika;
4) dzīves cikla analīze;
5) SEG emisiju aprēķini;
6) bibliometriskā analīze.

Promocijas darbā novērtēti un atlasītie risinājumi produktiem ar augstu pievienoto vērtību, izvērtējot augstāko iespējamo potenciālu.

Promocijas darba struktūra konceptuāli veidota kā zieda modelis, kur auglenīca simbolizē aprites ekonomikas centrālo jēdzienu un teorētisko kodolu. Ziedlapiņas attēlo dažādus aprites ekonomikas aspektus un to savstarpējās sakarības, kas kopumā veido sistēmisku skatījumu uz pētāmo problēmu. Katras ziedlapiņas atšķirīgā krāsa un forma norāda uz konkrētā elementa unikālo pienesumu kopējā koncepcijā, savukārt visa 'zieda' kopaina ilustrē aprites ekonomikas plašumu, integrētību un starpdisciplināro raksturu. Uzskatāma promocijas darba struktūra atspoguļota 1. attēlā.
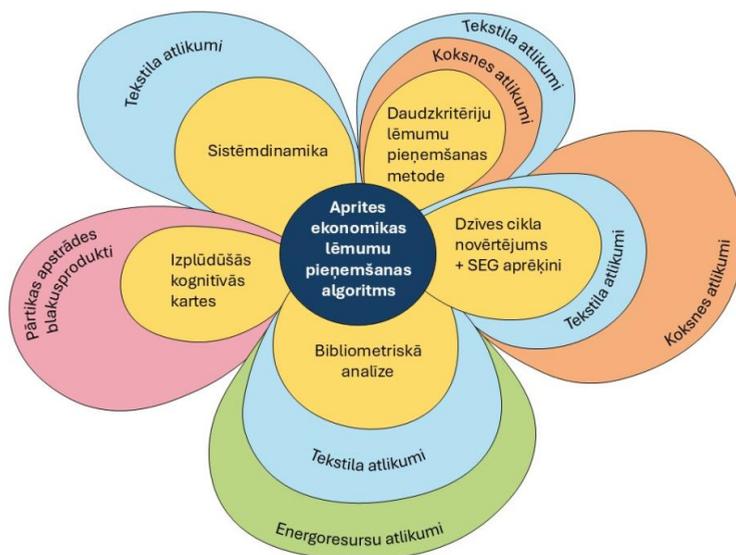
1. att. Promocijas darba struktūra.

Lai darbā iegūtie rezultāti būtu pēc iespējas plašāk izmantojami, izvērtējamie resursi tika izvēlēti iespējami dažādi un analizēts, kuri resursi rada vislielāko ietekmi uz vidi vai kuru apjoma pieauguma tendences ir ļoti ievērojamas. Darbā apskatīti šādi resursi:

1) tekstlila atlikumi;
2) kokapstrādes atlikumi;
3) pārtikas ražošanas blakusprodukti;
4) energoresursu atlikumi.

Darba struktūras sasaiste ar publikāciju kopu ir parādīta 2. attēlā. Resursu izpēte atspoguļota šādās publikācijās: "Analysis of Textile Circularity Potential", "CO$_2$ Storage in Logging Residue Products with Analysis of Energy Production Scenarios", "Unleashing Energy Potential: Insights of Energy Audit Practices", "What Drives the Circular Economy? Textile Sorting or Consumtion Reduction", "Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development". Tehnoloģiju izpēte atspoguļota šādās

publikācijās: "CO$_2$ Storage in Logging Residue Products with Analysis of Energy Production Scenarios", "Bioeconomy Towards Green Deal. Case Study of Citric Acid production Through Fuzzy Cognitive Maps". Savukārt produkta izpēte ir atspoguļota šādās publikācijās: "Analysis of Textile Circularity Potential", "Recycled Cross-laminated Timber as a Low Environmental Impact Alternative to Virgin Material: Latvia Case Study", "Uncertainty of Life Cycle Assessment Studies for Blended Textiles", "Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps".
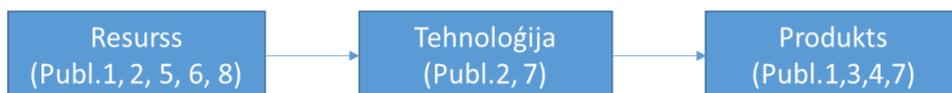
2. att. Darba struktūras sasaiste ar publikāciju kopu.

Tehnoloģiskās sistēmas risinājuma izvēles un ieviešana praksē, kā arī problēmu analīze, metodoloģijas lietojums un saistība ar promocijas darba analīzes līmeņiem ir apkopoti 1.tabulā. Publikācijās izmantotās metodes un iegūtie rezultāti veido promocijas darba pamatdaļu.

1. tabula

Promocijas darba metožu un publikāciju pārskats

Resurss	Metode	Publikācijas numurs	Publikācijas nosaukums
Tekstila atlikumi	Daudzkritēriju lēmumu pieņemšanas metode	1	Analysis of Textile Circularity Potential
Tekstila atlikumi	Daudzkritēriju lēmumu pieņemšanas metode	8	Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development
Kokapstrādes atlikumi	Daudzkritēriju lēmumu pieņemšanas metode un SEG (CO$_2$) emisiju aprēķini	2	CO$_2$ Storage in Logging Residue Products with Analysis of Energy Production Scenarios
Kokapstrādes atlikumi	Dzīves cikla novērtējums	3	Recycled Cross-laminated Timber as a Low Environmental Impact Alternative to Virgin Material: Latvia Case Study
Tekstila atlikumi	Dzīves cikla novērtējums un bibliometriskā analīze	4	Uncertainty of Life Cycle Assessment Studies for Blended Textiles
Energoresursu atlikumi	Bibliometriskā analīze	5	Unleashing Energy Potential: Insights of Energy Audit Practices
Tekstila atlikumi	Sistēmdinamika	6	What Drives the Circular Economy? Textile Sorting or Consumtion Reduction
Pārtikas apstrādes atlikumi	Izplūdušās kognitīvās kartes	7	Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps

Darba noslēgumā apspriesti pētījuma rezultāti, izdarīti secinājumi un izstrādātas rekomendācijas, lai ieviestu aprites ekonomikas modeli dažādās tautsaimniecības nozarēs.

Zinātniskā darba aprobācija

1. Analysis of Textile Circularity Potential. Valtere, M., Bezrucko, T., Blumberga, D. Environmental and Climate Technologies, 2023, 27(1), pp. 220–232.
2. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios. Viksne, G., Vamža, I., Terjanika, V., ... Pubule, J., Blumberga, D. Environmental and Climate Technologies, 2022, 26(1), pp. 1158–1168.
3. Recycled cross-laminated timber as a low environmental impact alternative to virgin material: Latvia case study Vasuks, P., Vamza, I., Valtere, M., Bezrucko, T., Blumberga, D. Case Studies in Construction Materials, 2025, 22, e04094.
4. Uncertainty of Life Cycle Assessment Studies for Blended Textiles. Valtere, M., Bezrucko, T., Poberznik, M., Vamza, I., Blumberga, D. Environmental and Climate Technologies, 2024, 28(1), pp. 794–811.
5. Unleashing Energy Potential: Insights of Energy Audit Practices. Liberova, V., Bremane, I., Lauka, D., ... Bezrucko, A.E., Blumberga, D. Energies, 2025, 18(3), 522.
6. What Drives the Circular Economy? Textile Sorting or Consumption Reduction Valtere, M., Bezrucko, T., Lauka, D., Blumberga, A., Blumberga, D. Circular Economy and Sustainability, 2025.
7. Bioeconomy towards green deal. Case study of citric acid production through fuzzy cognitive maps. Bezrucko, T., Lauka, D., Laktuka, K., ... Terjanika, V., Blumberga, D. Environmental and Climate Technologies, 2022, 26(1), pp. 684–696.
1. Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development. Valtere, M, Bezrucko, T., Liberova, V.,Blumberga, D. Environmental and Climate Technologies 2025, vol. 29, no. 1, pp. 323–343.

Referāti zinātnikās konferencēs:

1. XVIII International Scientific Conference of Environmental and Climate Technologies CONECT 2025, Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development
2. XVII International Scientific Conference of Environmental and Climate Technologies CONECT 2024Uncertainty of Life Cycle Assessment Studies for Blended Textiles
3. XVI International Scientific Conference of Environmental and Climate Technologies CONECT 2023Analysis of Textile Circularity Potential
4. XV International Scientific Conference of Environmental and Climate Technologies CONECT 2022 Bioeconomy Towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps;
5. XV International Scientific Conference of Environmental and Climate Technologies CONECT 2022 CO2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios

1. LITERATŪRAS APKOPOJUMS

1.1. Aprites bioekonomikas pamatprincipi

Cilvēce turpina patērēt dabas resursus un pakalpojumus neilgtspējīgi, pārsniedzot ātrumu, ar kādu šie resursi var vairoties un/vai atjaunoties, tādējādi palielinot spiedienu uz klimatu, ekosistēmām, dzīvotnēm un bioloģisko daudzveidību [76]. Zaļā kursa mērķis ir risināt klimata pārmaiņu problēmas, cenšoties pārvērst 27 valstu bloku par taisnīgu un plaukstošu sabiedrību ar modernu, resursefektīvu, konkurētspējīgu, zemu oglekļa dioksīda emisiju ekonomiku, aizsargāt un stiprināt ES dabas kapitālu un uzlabot dzīves kvalitāti pašreizējām un nākamajām paaudzēm [77], [78], [79]. Kopējie mērķi, ko izvirzījusi ES, ir [78], [79]:

- sasniegt klimatneitralitāti līdz 2050. gadam;
- aizsargāt cilvēku dzīvību, dzīvniekus un augus, samazinot piesārņojumu;
- palīdzēt uzņēmumiem kļūt par pasaules līderiem tīru produktu un tehnoloģiju jomā;
- nodrošināt taisnīgu un iekļaujošu pielāgošanos.

ES izaugsmes stratēģija norāda uz nepieciešamību ātri mainīt pašreizējo situāciju, ieguldīt finanšu resursus pētniecībā, veicināt inovācijas, nodrošināt tīru enerģiju, stimulēt nozares pāreju uz tīru ekonomiku, rīkoties energoefektīvi un resursefektīvi, atrast risinājumus pārtikas drošībai un dabas resursu pārvaldībai, samazināt klimata pārmaiņas un atkarību no fosilajiem resursiem, palielināt Eiropas konkurētspēju, radīt jaunas darba vietas un veicināt bioekonomiku [76], [80], [81]. Mūsdienās bioekonomika tiek uzskatīta ne tikai par bioresursu ekonomiku, bet arī par ilgtspējīgu bioresursu patēriņu, kas rada pievienoto vērtību sabiedrībai. Lai gan ES Direktīvā 2008/98/EK ir noteikts, ka ražošanas blakusprodukti netiek klasificēti kā atkritumi, uzņēmumos tos bieži uzskata par tādiem un nosūta uz atkritumu plūsmām vai zemas vērtības plūsmām, piemēram, biogāzes vai cietā kurināmā ražošanai [30]. Bioekonomikas attīstība, balstoties uz inovāciju prasmēm un ieguldījumiem zināšanās, ir neizbēgami nepieciešama, lai sasniegtu lielu daļu no izvirzītajiem mērķiem [82]. Bioekonomikas pamatā ir trīs ilgtspējīgas attīstības principi: ekonomika, sabiedrība un daba. Šiem trim fundamentālajiem principiem jāveido slēgts cikls, kurā procesa blakusprodukts (atkritumu produkts) ir cita procesa izejmateriāls [30]. Šāda pieeja bioekonomikai palielina un uzlabo produktu pievienoto vērtību, aizstāj fosilos kurināmos enerģijas ražošanā un samazina SEG emisijas. Promocijas darba mērķis ir radīt un piedāvāt bioekonomikas iespējas, demonstrējot, analizējot un aprakstot iespējamos risinājumus ar dažādu piemēru palīdzību. Tas ir ilustratīvs un demonstratīvs pētījums par to, kā radīt iespējamos bioekonomikas risinājumus, kas veicinātu Zaļā kursa mērķu sasniegšanu un būtu piemēroti ieviešanai Latvijā.

1.2. Tekstilrūpniecības aprites ekonomika

Tekstilizstrādājumi ir vieni no pasaulē senākajiem un visplašāk izmantotajiem mākslīgajiem materiāliem. Tekstilizstrādājumus izmanto ne tikai apģērbā, bet arī veselības aprūpē, transportā, būvniecībā un citās jomās [3]. Pēdējo divu desmitgažu laikā globālā

tekstilizstrādājumu ražošana un patēriņš ir dubultojies [1], radot negatīvu ietekmi uz vidi, jo tekstilrūpniecība ir ļoti piesārņojoša. Pašlaik tekstila sistēmā plaši izmanto aprites ekonomikas prakses, un tās pamatā galvenokārt ir lineārās ekonomikas modelis. Tomēr tekstila sistēmai ir liels aprites ekonomikas potenciāls, jo lielāko daļu materiālu varētu pārstrādāt vai atkārtoti izmantot. Ieviešot aprites ekonomiku modes tekstila vērtību ķēdē, varētu panākt, ka 95 % tekstilizstrādājumu tiek atgriezti piegādes ķēdē [4]. Pieaug pētījumu skaits par ilgtspējību un aprites ekonomikas potenciālu tekstila nozarē [59], kas aplūko dažādus aspektus, piemēram, ekomarķējumu [18], patērētāju iesaisti [14], aprites piegādes ķēdi [60] un atkritumu apsaimniekošanu [61], [62]. Tomēr var novērot būtiskus trūkumus: datu nenoteiktība, novecojuši dati vai datu trūkums. Pētījumi atklāj neatbilstības datos dažādos aspektos, piemēram, globālajā emisiju daļā un apģērbu patēriņā. Piemēram, tekstila nozares emisiju daļa no kopējām globālajām emisijām literatūrā svārstās no 3 % līdz 10 % [3], [63], [64]. Nozarei arī trūkst aktuālu datu. Piemēram, ES kontekstā jaunākie dati par atkritumiem, emisijām un resursu patēriņu ir no 2020. gada [65]. Taču šie dati atspoguļo *COVID-19* pandēmijas ietekmi, kas šobrīd var nebūt aktuāla, un trūkst vairāku datu, piemēram, tekstilizstrādājumu šķirošanas rādītāja. Nākamie jaunākie dati ir no 2018. gada [66]. Literatūrā ir vērojams arī datu trūkums. Kopumā ir pieejami dati par patēriņu, šķiroto tekstilizstrādājumu daļu un tekstilizstrādājumiem, kas nonāk atkritumu plūsmā. Tekstila nozares galvenie aprites ekonomikas rādītāji ir apkopoti 1.1. tabulā. Šie rādītāji ir visatbilstošākie aprites ekonomikai tekstila nozarē. Tomēr trūkst datu par tekstilizstrādājumu daudzumu ražošanā un mazumtirdzniecībā un par tiem izstrādājumiem, kas pēc patēriņa tiek iznīcināti. Tas ir būtisks datu trūkums, jo šis rādītājs un tā prognozētais pieaugums sniedz ieskatu par aprites ekonomikas potenciālu tekstilizstrādājumu dzīves ciklā.

1.1. tabula.

Aprites ekonomikas galvenie rādītāji tekstila nozarē un to prognozes

	Bāze	Plānotās pārmaiņas tuvā nākotnē
Apģērba patēriņš	4,38 miljoni tonnu gadā [66]	+ 63 % [67]
Apģērba mūžs	3,3 gadi [68]	− 50 % [69]
Tekstila šķirošanas ātrums	38 % [66]	+ 33–90 000 tonnas gadā [66]
Tekstils, kas izmests jauktā atkritumu plūsmā pēc patēriņa	3,3–3,7 miljonu tonnas gadā [66]	Nav zināms

Ir vairāki iespējamie ceļi, lai sasniegtu ES aprites ekonomikas mērķus [42], ar diviem galvenajiem izaicinājumiem tekstila sistēmā: uzlabot šķirošanu un pārstrādi, kā arī samazināt patēriņu. Tekstilrūpniecībā liels uzsvars tiek liekts uz šķirošanu un pārstrādi. Šie procesi ir savstarpēji saistīti: efektīvai pārstrādei nepieciešama augstas kvalitātes savākšana un šķirošana, savukārt pārstrādes uzlabojumi var palielināt šķirošanas rentabilitāti [70].

Galvenais savākšanas un šķirošanas izaicinājums ir pašā biznesa modelī. Nozarē trūkst struktūras un skaidras komunikācijas starp ieinteresētajām pusēm, kas padara sistēmu neefektīvu un var radīt izmaksas, kas pārsniedz ieņēmumus [71]. Pašlaik lielākā daļa ieņēmumu

nāk no tekstilizstrādājumu tālākpārdošanas atkārtotai izmantošanai, nevis no pārstrādes [72]. Turklāt augstas kvalitātes savākšanas un šķirošanas infrastruktūra ir nepietiekami attīstīta, un trūkst arī tehnoloģisko risinājumu, jo šķirošana joprojām lielā mērā ir manuāla un rada izaicinājumus, jo atkritumu plūsmas turpina pieaugt [71].

Savukārt slēgtās cilpas pārstrāde saskaras galvenokārt ar tehniskām problēmām, īpaši, ja runa ir par jauktām šķiedrām. Nepieciešami tehnoloģiskie uzlabojumi, kā arī uzlabota informācija par tekstilizstrādājumu sastāvu un iespējamiem piesārņotājiem [72]. Turklāt tekstilizstrādājumi var radīt pārstrādes problēmas piesārņojuma vai slikta sākotnējā dizaina dēļ. Pastāv arī ierobežoto pārstrādes ciklu problēma, kas prasa inovatīvas pieejas, jo mehāniski pārstrādāta kokvilna ar īsām šķiedrām var pat neizturēt otro pārstrādes ciklu [72].

Otrais lielais izaicinājums un galvenais tekstila sistēmas virzītājspēks ir patēriņš. Šajā nozarē patēriņš ir īpaši neilgtspējīgs un strauji augošs. Ātrā mode un pārmērīgs patēriņš ir centrālais jautājums, jo augsts pieprasījums veicina ātrās modes tendences un padara tekstilizstrādājumus pieejamākus [73]. Ātrā mode radās, kad lielie zīmoli sāka izmantot ražošanu zemākas izmaksas valstīs, piemēram, Indijā un Ķīnā [73]. Šī pāreja izraisīja ražošanas apjomu strauju pieaugumu, veicinot gan vides, gan sociālos traucējumus. Ātrā mode prioritizē apjomu pār dizainu, kvalitāti un produkta kalpošanas laiku, tomēr neilgtspējīgs pieprasījums ir visa pamatā.

Patērētāju uzvedība rada būtisku izaicinājumu ilgtspējības un aprites ekonomikas prakses ieviešanai tekstilrūpniecībā. Tā ir sarežģīta, un to ietekmē vairāki faktori, piemēram, iekšējie faktori, personība un motivācija, ārējie faktori, tostarp kultūra un sociālās grupas, situācijas ietekmes, piemēram, politiskie un ekonomiskie apstākļi, un mārketinga faktori arī cena un reklāma [74]. Ņemot vērā šo sarežģītību, patērētāju uzvedības izpratne un maiņa ir būtiska, lai veicinātu aprites ekonomiku tekstila nozarē.

Pētījumos visbiežāk uzmanība tiek pievērsta tekstilizstrādājumiem kopumā vai tikai apģērbam. Iepriekš nebija veikti pētījumi par tekstilizstrādājumu grupām to izmantošanas kontekstā aprites ekonomikā, tāpēc tika veikts pētījums, salīdzinot un analizējot aprites ekonomikas attīstības iespējas trīs tekstilizstrādājumu grupās: modes, mājas un tehniskie tekstilizstrādājumi [75]. Rezultāti parādīja, ka modes tekstilizstrādājumiem ir vislielākais potenciāls aprites ekonomikai, tāpēc nākamajā pētījumā analizēta tieši apģērbu vērtību ķēde.

1.2.1. Tekstilšķiedras

Tekstilrūpniecībai ir būtiska ietekme uz vidi, jo ražošana ir resursietilpīga un tekstilizstrādājumu pieprasījums ir augsts [41]. ES tekstilizstrādājumi ir trešā lielākā kategorija zemes un ūdens izmantošanas ziņā un ceturtā lielākā kategorija negatīvās ietekmes uz vidi un klimata pārmaiņu ziņā [42]. Šī ietekme tikai pieaugs, jo, turpinot pašreizējo biznesa pieeju, visticamāk, strauji pieaugs patēriņš. Tekstilizstrādājumu ražošana ir visietekmīgākā to dzīves cikla daļa, jo tā patērē lielu daudzumu enerģijas, ūdens un ķīmisko vielu [43], [44]. Kopumā šī ietekme var veidot gandrīz 70 % no kopējās dzīves cikla ietekmes uz vidi: šķiedru ražošana (38 %), dzijas ražošana (8 %), auduma ražošana (6 %) un mitrā apstrāde (15 %) [45]. Tomēr tas ir atkarīgs no šķiedru veida, apstrādes metodēm un tehnoloģijām.

Tekstilizstrādājumus var izgatavot no mākslīgām, dabīgām un jauktām šķiedrām. Visbiežāk izmantotā dabīgā šķiedra tekstilizstrādājumu ražošanā ir kokvilna, kas veido 23 % no visām pasaulē ražotajām šķiedrām [4]. Neskatoties uz dabisko izcelsmi, kokvilnas ražošanai ir būtiska negatīva ietekme uz vidi un sabiedrību. Šo ietekmi izraisa intensīva zemes, ūdens, pesticīdu un ķīmisko vielu izmantošana ražošanas procesā [46].

Mākslīgās šķiedras var klasificēt pēc to polimēru izcelsmes: dabiskie un sintētiskie polimēri [46]. Poliesteris ir visplašāk izmantotā sintētiskā šķiedra, veidojot 52 % no tekstilšķiedrām [4]. Vides problēmas galvenokārt saistītas ar atkarību no fosilajiem resursiem materiālu un enerģijas iegūšanai [47]. Poliesteru tekstilizstrādājumu ražošanā kaitīgās ķīmiskās vielas un krāsvielas bieži tiek iegūtas arī no fosilajiem resursiem. Vēl viena problēma ar sintētiskajiem tekstilizstrādājumiem ir mikroplastmasas veidošanās to lietošanas laikā un dzīves cikla beigās [2].

Jauktie tekstilizstrādājumi tiek plaši izmantoti, jo divu vai vairāku šķiedru tipu sajaukšana nodrošina kombinētas un unikālas īpašības [48]. Visizplatītākais jauktais tekstilizstrādājums tirgū ir kokvilna/poliesteris (*CO/PES*), kas tiek izmantots dažādās proporcijās. Šis maisījums ir tik populārs un plaši izmantots ikdienas apģērbā, jo poliesteris nodrošina izturību, pretkroku īpašības, ātru žūšanu un formas saglabāšanu, savukārt kokvilna piedāvā komfortu, mitruma kontroli un auduma elpojamību [49]. Tomēr, kad jauktais tekstilizstrādājums sasniedz dzīves cikla beigas, rodas būtiskas problēmas, jo dažādie maisījumi un sarežģītās struktūras padara pārstrādi sarežģītu [48]. Kokvilnas un poliestera maisījumi nav izņēmums. Turklāt dažādās maisījumu procentuālās attiecības neļauj izveidot standartizētu sistēmu to atdalīšanai un pārstrādei.

Visplašāk izmantotā metode produkta ietekmes uz vidi novērtēšanai ir aprites cikla novērtējums (ACN) [50]. Analīze var aptvert visu dzīves ciklu, sākot no izejvielu ieguves līdz dzīves cikla beigām, piemēram, iznīcināšanai vai pārstrādei. ACN metodi izmanto arī tekstilizstrādājumu novērtēšanai. Ir veikti daudzi ACN pētījumi, lai novērtētu tekstilizstrādājumus, ņemot vērā tādus mainīgos lielumus kā šķiedra, apstrādes metodes un ražotā tekstilizstrādājuma veids [51], [52], [53]. Daži pētījumi koncentrējas arī uz konkrētu dzīves cikla posmu [54], [55].

1.2.2. Tekstilatkritumi kā resurss

Iedzīvotāju skaita pieaugums, dzīves līmeņa uzlabošanās un tekstilizstrādājumu kalpošanas laika samazināšanās pēdējos divdesmit gados ir veicinājusi tekstilizstrādājumu patēriņa un līdz ar to arī ražošanas divkāršu pieaugumu pasaulē [1]. Tam ir negatīva ietekme uz vidi, jo tekstilrūpniecība ir ļoti piesārņojoša, resursu ietilpīga un rada daudz atkritumu. Visā aprites ciklā aptuveni 87 % no ievadītajām šķiedrām nonāk izgāztuvēs, un mazāk nekā 1 % tiek pārstrādāts atpakaļ tekstilizstrādājumos. Zaudētās iespējas 2017. gadā tika novērtētas vairāk nekā 93 miljardu EUR apmērā [2].

Tekstilrūpniecības nozarei ir liela nozīme pārejā uz klimatneitralitāti. Pētījumos secināts, ka tekstilrūpniecība ir atbildīga par lielu daļu no pasaules oglekļa emisijām [3]. Tekstilrūpniecības sistēmai pārejot no lineārās [2] uz aprites ekonomikas sistēmu, lielāko daļu tekstilizstrādājumu potenciāli varētu pārstrādāt vai atkārtoti izmantot. Piemēram, ja modes

tekstilizstrādājumu vērtību ķēdē tiktu ieviesta aprites ekonomika, aptuveni 95 % modes tekstilizstrādājumu varētu atgriezt atpakaļ piegādes ķēdē – vairāk nekā 60 % no visiem apģērbiem varētu izmantot atkārtoti, 35 % pārstrādāt un tikai 5 % noglabāt poligonā [4].

Pāreja no lineārās uz aprites ekonomiku ir nepieciešamība. Mūsu sabiedrība patērē vairāk, nekā Zeme spēj saražot. To parāda "Zemes pārslodzes diena" (angļu val. *Earth Overshoot Day*), kas katru gadu norāda datumu, kad tiek izsmelti visi dabas resursi, kas varētu atjaunoties šajā pašā gadā. 2022. gadā tas bija 28. jūlijs [5]. Aprites ekonomikas būtība ir novērst atkritumu rašanos visās sistēmās, pagarinot produkta dzīves ciklu, labojot, atkārtoti izmantojot un pārstrādājot [6]. ES tekstilizstrādājumu produktu grupu ir noteikusi kā vienu no septiņām galvenajām produktu vērtību ķēdēm, kurām pārejā uz aprites ekonomiku tiks piešķirta prioritāte [7]. Turklāt aprites ekonomikas attīstība tekstilrūpniecības nozarē atbilst vismaz sešiem no septiņpadsmit Apvienoto Nāciju Organizācijas ilgtspējīgas attīstības mērķiem (3.; 6.; 8.; 9.; 12.; 14. mērķis) [8].

Trīs galvenās tekstilizstrādājumu plūsmas ir modes, mājas un tehniskais tekstils. Modes tekstilizstrādājumi ietver apģērbus un apavus, bet šajā pētījumā galvenā uzmanība pievērsta apģērbiem. Šī kategorija ir vislielākā, tā veido aptuveni 60 % no kopējā tekstilizstrādājumu apjoma, un paredzams, ka tāda tā arī paliks [2]. Mājas tekstilizstrādājumi ietver visus tekstilizstrādājumus, ko izmanto iekštelpām un mēbelēm. Šajā pētījumā galvenā uzmanība pievērsta gultas, un virtuves veļai, piemēram, gultasveļai, dvieļiem un galdautiem. Mājas tekstilizstrādājumu patēriņš laika gaitā ir bijis samērā stabils. 2020. gadā tas nedaudz palielinājās, bet apģērbu patēriņš samazinājās [9]. To var izskaidrot ar *COVID-19* pandēmiju. Tehniskais tekstils ietver audumus, kuru galvenie kritēriji ir funkcionalitāte, nevis askētisms. Šos tekstilizstrādājumus izmanto daudzās nozarēs, piemēram, būvniecībā, automobiļu, aviācijas, sporta, aizsardzības un lauksaimniecības nozarē. To plašā lietojuma dēļ tā ir strauji augoša tekstilizstrādājumu kategorija [10].

Ir daudz pētījumu par ilgtspēju un iespējām pāriet uz aprites ekonomiku tekstilrūpniecības nozarē [13]. Autori aplūko tādas tēmas kā patērētāju uzvedība [14], tekstilizstrādājumu pārstrāde un atkārtota izmantošana [4], ietekme uz vidi [15], atkritumu veidošanās nozarē [16], konkrēta tekstilizstrādājuma aprites cikla novērtējums [17], ekomarķējums [18] utt. Lielākā daļa šo pētījumu ir vērsti uz visu tekstilrūpniecības nozari vai tikai uz modes tekstilizstrādājumiem. Tomēr, cik zināms, nav apkopota informācija par katru tekstilizstrādājumu grupu atsevišķi, un aprites ekonomikas attīstības iespējas visos šajos segmentos nav analizētas. Ņemot vērā minēto, šī pētījuma mērķis ir apkopot informāciju no zinātniskās literatūras un izvērtēt, kurai tekstilizstrādājumu grupai ir vislielākais aprites ekonomikas izaugsmes potenciāls, pamatojoties uz ekonomiskajiem, vides, sociālajiem un tehniskajiem kritērijiem.

Tekstila ražošana un patēriņš pasaulē pieaug, un līdz ar to palielinās arī tekstila atkritumu apjoms [1]. Pašlaik aptuveni 75 % apģērba atkritumu pasaulē tiek noglabāti poligonos vai sadedzināti, 25% tiek pārstrādāti vai atkārtoti izmantoti, bet tikai 1% tiek pārstrādāts atpakaļ tekstilmateriālos [2]. Tādējādi pāreja uz aprites ekonomiku tekstila nozarē ir cieši saistīta ar vairākiem Apvienoto Nāciju Organizācijas ilgtspējīgas attīstības mērķiem [3], īpaši ar 12. mērķi – atbildīgu patēriņu un ražošanu.

Tekstila atkritumu problēma ir aktuāla arī ES, kur šī nozare ierindojas ceturtajā vietā pēc ietekmes uz primāro izejvielu un ūdens patēriņu un piektajā – pēc ietekmes uz siltumnīcefekta gāzu emisijām [4]. Ņemot to vērā, ES tekstilu ir iekļāvusi starp septiņām galvenajām produktu vērtību ķēdēm, kuras jātransformē aprites ekonomikas virzienā. Šīs pārejas ietvaros Atkritumu pamatdirektīva paredz, ka no 2025. gada 1. janvāra visās ES dalībvalstīs jāievieš atsevišķa tekstila atkritumu savākšana [5]. Tomēr atsevišķā savākšana ir tikai pirmais solis – šķirošana un pārstrāde ES vēl joprojām nav pietiekami attīstīta [6]. Ja netiks vienlaikus attīstīta arī šķirošanas un pārstrādes kapacitāte, pastāv risks, ka sašķirotais tekstils joprojām tiks sadedzināts, noglabāts vai eksportēts ārpus ES kā atkritumi [7].

Tekstila atkritumus klasificē trīs galvenajās plūsmās: pēcražošanas, pirmspatēriņa un pēcpatēriņa atkritumos [1]. Pēcražošanas atkritumi rodas ražošanas procesā, pirmspatēriņa atkritumi ir produkti, kas nav pārdoti vai ir bojāti, bet nav lietoti, savukārt lielākā pēc patēriņa atkritumu daļa veidojas pēc lietošanas. ES vidēji uz vienu iedzīvotāju gadā rodas 15 kg tekstila atkritumu, no kuriem 85 % ir patērētāju izmesti apģērbi un mājas tekstils, t. i., pēcpatēriņa atkritumi [6]. Šie atkritumi sastāv no dažādu tekstilu maisījuma, galvenokārt kokvilnas un poliestera, ar papildu elementiem, piemēram, pogām un rāvējslēdzējiem, kā arī vielām, piemēram, krāsvielām, pārklājumiem un liesmu slāpētājiem [8], [9]. Šīs īpašības apgrūtina tekstila pārstrādi ar šobrīd pieejamajām tehnoloģijām.

Viens no iespējamajiem risinājumiem ir šķirošanas uzlabošana, lai nodrošinātu maksimāli tīras tekstila plūsmas, kas piemērotas pārstrādei. Tomēr ceļā uz to pastāv vairāki šķēršļi. Šobrīd šķirošana lielākoties notiek manuāli, padarot to laikietilpīgu un dārgu [9]. Turklāt tekstils reti sastāv no vienmateriāla šķiedrām – tekstila atkritumi ir daudzkomponentu un bieži jaukti materiāli. Tos iespējams klasificēt vairāk nekā 300 dažādās kategorijās atkarībā no izmēra, sastāva un šķiedru veida [1]. Daži no tiem ir grūti pārstrādājami vai prasa specializētas tehnoloģijas. Tāpat arī atkritumu kvalitāte nav garantēta, jo tekstils var būt bojāts vai piesārņots [1]. Šo šķēršļu dēļ rodas jautājums, vai ir iespējams pārstrādāt jauktos tekstila atkritumus kā vienotu plūsmu bez plašas iepriekšējas šķirošanas.

Lai gan ir veikti daudzi pētījumi par dažādu tekstilu, tostarp jaukto tekstilu, pārstrādi [10], [11], [12], [13], [14], [15], tomēr netika atrasts pētījums, kas vispusīgi apkopotu pieejamās zināšanas par pēcpatēriņa jauktā tekstila atkritumu pārstrādi. Šobrīd arī nav pieejamu komerciāli dzīvotspējīgu tehnoloģiju, kas ļautu pārstrādāt jauktos tekstilus atpakaļ tekstilmateriālos vai augstas pievienotās vērtības produktos.

Neskaidrs ir jautājums, vai pastāv tādi produkti, kurus varētu iegūt no pēcpatēriņa jauktajiem tekstila atkritumiem. Ja tādi produkti pastāv, būtu jāvērtē, kurš no tiem būtu vispiemērotākais turpmākai attīstībai, balstoties uz ekonomiskiem, vides, sociāliem un tehniskiem faktoriem. Produktu identificēšanai izmantota literatūras analīze, bet salīdzināšanai un izvērtēšanai tika piemērota daudzkritēriju lēmumu pieņemšanas metode, kas ļauj pamatoti izvērtēt dažādus risinājumus pēc noteiktiem kritērijiem [16], [17].

1.3. Kokrūpniecības aprites ekonomika. SEG emisiju mazināšana

1.3.1. Koksnes resurss

Ilgtspējība tiek apskatīta daudzos cilvēkiem nozīmīgos sektoros. Viens no šiem sektoriem ir tekstilrūpniecība, kas pieminēta iepriekšējā nodaļā. Arī mežsaimniecības sektorā tiek aktīvi izvērtēta ilgtspējība. Mežsaimniecības nozarē no mežsaimniecībā iegūstamās ražas rodas liels daudzums atkritumu un atlieku. Tas var radīt ievērojamas apsaimniekošanas problēmas, jo izmestā biomasa var kaitēt videi. Tikmēr, pieaugot pasaules iedzīvotāju skaitam un palielinoties pieprasījumam pēc būvniecības produktiem un materiāliem, ir nepieciešami ilgtspējīgi enerģijas avoti un izejvielas. Mežsaimniecības atkritumi un mežizstrādes atlikumi ir nepietiekami izmantoti resursi enerģijas un materiālu ražošanai. Līdz šim ir veikts maz pasākumu, lai šos resursus izmantotu "zema oglekļa satura" veidā. Tiek lēsts, ka uz katru kubikmetru nocirstas koksnes mežā paliek kubikmetrs atkritumu un atlikumu (piemēram, celmi, zari, zaļumi). Pašlaik no visas pasaulē saražotās koksnes biomasas 20 % var uzskatīt par primārās produkcijas zudumiem, kas atstāti mežā, lai sadalītos, un ko varētu izmantot kā izejvielu dažādu produktu ražošanā, tostarp kurināmā, polimēru, būvmateriālu un izstrādājumu ražošanā [19].

Koksnei un no tās izgatavotiem izstrādājumiem ir svarīga priekšrocība salīdzinājumā ar citiem būvmateriāliem – tie ir būtisks CO_2 piesaistes avots. Novērots, ka pastāv tieša korelācija starp piesaistītā CO_2 daudzumu un no koksnes iegūtās biomasas daudzumu, kas tiek novākta, lai ražotu augstas pievienotās vērtības produktus. Palielinoties novāktās koksnes daudzumam vai pieaugot koksnes izmantošanas efektivitātei, palielinās arī oglekļa piesaistīšanas apjoms [20]. Kopējos dekarbonizācijas risinājumus var panākt, ja tiek īstenoti ilgtspējīgi oglekļa cikli, tostarp izmantojot oglekļa uztveršanas un izmantošanas tehnoloģijas (sk. 1.1. attēlu) [21], [22], [23], [24].
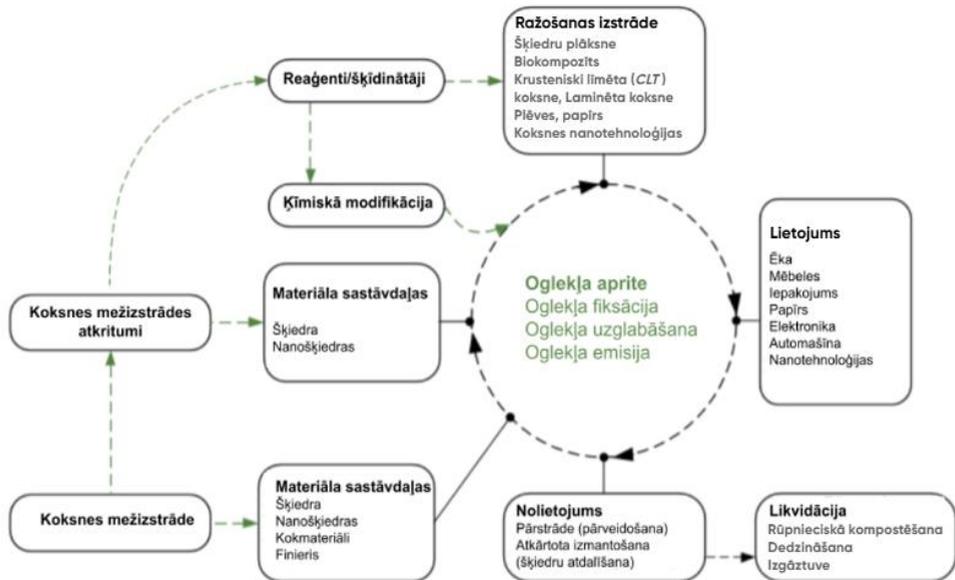
1.1. attēls. Ilgtspējīgs koksnes ciršanas atlikumu oglekļa cikls [19].

Koksnes izstrādājumu nozarē ievērojamu CO_2 sekvestrācijas potenciālu var saistīt ar koksnes plātņu un koksnes inženierijas izstrādājumu ražošanu [25], [26]. 2017. gadā veiktajā pētījumā par oglekļa uzglabāšanu koksnes produktos aplūkots oglekļa sekvestrācijas potenciāls trim dažādiem koksnes plātnēm: orientēto skaidu plātnēm (*OSB*), skaidu plātnēm (*PB*) un vidēja blīvuma kokskaidu plātnēm (*MDF*). Saskaņā ar *IPCC* metodoloģiju visi šie trīs produkti ir iekļauti valstu inventarizācijas ziņojumos kā nocirstas koksnes produkti, kas uzkrāj oglekli, tādējādi samazinot kopējo CO_2 bilanci atmosfērā. Aprēķināts, ka kubikmetrs *PB* un *OSB* plātņu sekvestrē 720 kg CO_2 katrs un ka kubikmetrs *MDF* sekvestrē 820 kg CO_2, ņemot vērā materiālu ražošanas radīto emisiju skaitu [27].

Tomēr, neraugoties uz šo priekšrocību, šādu plātņu ražošana ir diezgan energoietilpīga. Labāko pieejamo tehnisko paņēmienu (LPTP) atsauces dokumentā koksnes plātņu ražošanai norādīts, ka vidējais siltumenerģijas daudzums, kas nepieciešams viena kubikmetra materiāla ražošanai, ir 0,955 MWh *PB* plātnēm, 0,4 MWh – *OSB* plātnēm un 1,65 MWh – *MDF* plātnēm. Vidējais elektroenerģijas daudzums, kas nepieciešams viena kubikmetra materiāla ražošanai, ir 0,155 MWh *PB*, 0,115 MWh – *OSB* un 0,505 MWh – *MDF* plātnēm [27], [28]. Savukārt tādu siltumizolācijas materiālu kā *Ecowool* un minerālvates ražošanai ir nepieciešams 0,00416 MWh un 0,200 MWh elektroenerģijas vienam kubikmetram produkta. Lai gan cietās plātnes ir populārs siltumizolācijas materiāls, tās lielākoties ražo no putupolistirola vai poliuretāna putām. Abas ražo no fosilajiem resursiem, izslēdzot iespēju šādos produktos uzkrāt CO_2. Tomēr arvien populārākas kļūst cietās un lokanās plātnes no koksnes šķiedrām. Šādu materiālu ražošanas tehnoloģija ir līdzīga citiem kokšķiedras materiāliem, kas sīkāk aprakstīti turpmāk.

Lai gan viena kubikmetra cietās plātnes izolācijas materiāla CO_2 sekvestrācijas ieguvumi būs mazāki nekā *OSB*, *PB* un *MDF* plātnēm, ņemot vērā zemāku koksnes blīvumu materiālā, tā ražošanai būs nepieciešams mazāk enerģijas un izejvielu. Latvijā un daudzās citās valstīs zemas efektivitātes un nesiltinātu ēku joprojām ir daudz, kas nozīmē, ka ēku siltumizolācijas materiāli pārskatāmā nākotnē joprojām būs pieprasīts produkts. Mūsdienās ir pieejams plašs siltumizolācijas materiālu klāsts, un katram no tiem ir savas priekšrocības un trūkumi. Tomēr mūsdienu patērētājiem rūp ne tikai materiāla fizikālās un mehāniskās īpašības, bet arī ietekme uz vidi. Izolācijas materiālu ražošana varētu kļūt par vienu no Latvijas mežsaimniecības nozares nākotnes iespējām. Mežizstrādes un ražošanas procesā neizbēgami rodas blakusprodukti un atlikumi. Šobrīd mežsaimniecības uzņēmumi šos blakusproduktus galvenokārt izmanto enerģijas ražošanai vai pārdod citiem uzņēmumiem. Šo blakusproduktu eksports joprojām ir neefektīvs, jo šobrīd tos pārdod kā produktus ar zemu pievienoto vērtību. Tā kā mežsaimniecības nozares uzņēmumi cenšas palielināt ražošanas efektivitāti un produktivitāti, atkritumu un atlikumu, kas iepriekš tika uzskatīti par mazvērtīgiem, izmantošana kļūst arvien pievilcīgāka. Šo blakusproduktu izmantošana siltumizolācijas ražošanā ir viens no potenciālajiem risinājumiem, kā palielināt to vērtību [29], [30].

Pēdējās desmitgadēs CO_2 emisiju mazināšana ir kļuvusi par vienu no svarīgākajiem jautājumiem, tāpēc ir ļoti svarīgi izprast procesus lauku CO_2 ekonomikas nozarēs, faktorus, savstarpējās saiknes un ietekmi uz vidi un dabas kvalitāti, kā arī turpmākās darbības pamatnostādnes. CO_2 pārstrāde, tostarp tieša uztveršana, pārveidota CO_2 pārstrāde vai iepriekš apstrādāta CO_2 otreizēja izmantošana, var pozitīvi ietekmēt CO_2 emisiju samazināšanu un lauku teritoriju attīstību [21], [22], [23], [24]. Izmaiņas koksnes atkritumu apstrādes praksē un cieto plātņu ražošana no mežizstrādes atlikumiem var pozitīvi ietekmēt CO_2 emisiju samazināšanu, nodrošinot tā uzkrāšanu produktos. Šī darba mērķis ir analizēt izolācijas materiāla ietekmi uz vidi. Nepietiekami novērtēta resursa izmantošana siltumizolācijas materiāla ražošanai var būt dzīvotspējīga no ekonomiskā un tehnoloģiskā viedokļa. Šī prakse varētu būt izdevīga no produktu pieprasījuma un izejvielu piegādes viedokļa, pievienojot vērtību koksnes vērtību ķēdei.

1.3.2. Koksnes atlikumu lietojums būvniecībā

Būvniecības nozare veido 40 % no ikgadējām oglekļa dioksīda emisijām pasaulē, ko lielā mērā nosaka izmantotie būvmateriāli, jo īpaši tērauda un betona ražošana un izmantošana. Abi šie materiāli ir pazīstami kā materiāli ar lielu ietekmi uz vidi [31]. Tāpēc Zaļais kurss un citas iniciatīvas cenšas panākt izmaiņas šajā nozarē, izvirzot mērķus, lai sasniegtu zemāku emisiju līmeni. Mērķus varētu sasniegt, uzlabojot ražošanas tehnoloģiju efektivitāti vai izstrādājot un izmantojot jaunus materiālus ar mazāku emisiju ietekmi. Šķērsām līmētā koksne (*CLT*) tirgū ir pieejama jau aptuveni 30 gadus. Tā ir izrādījusies daudzsološs alternatīvs materiāls betonam un tēraudam, jo *CLT* mehāniskās īpašības ir pietiekamas, lai to varētu izmantot kā konstrukcijas materiālu, un būvniecības izmaksas, izmantojot CLT, ir konkurētspējīgas salīdzinājumā ar populārākajiem būvniecības paņēmieniem, izmantojot tēraudu un betonu [32]. Ēku būvniecība ar *CLT* kļūst arvien populārāka klimata apsvērumu dēļ – atjaunojamā materiāla un oglekļa uzglabāšanas potenciāla dēļ, aizstājot energoietilpīgo betona ražošanu [33]. Līdz ar *CLT*

izgudrošanu būvēšana no koka ir atguvusi savu popularitāti, koksnes izmantošanas gadījumi ir paplašinājušies līdz vidēja augstuma ēkām [34].

Līdz ar Zaļā kursa ieviešanu pat klimatam labvēlīgās *CLT* ēkas ir bijušas pakļautas lielākai aprites principu ienākšanai šajā būvniecības nozarē. Aprites princips *CLT* ēkās ir iekļauts vairākos veidos. Ir svarīgi iekļaut *CLT* vispārējos ēku otrreizējās pārstrādes centienos, kuru mērķis ir uzlabot nojaukto ēku materiālu atkārtotu izmantošanu. Lai gan tuvākajos gados no *CLT* izgatavotās ēkas netiks nojauktas lielā apjomā, jo salīdzinoši nesen uzsākta būvniecība ar *CLT* [32], pienāks laiks, kad *CLT* ēku kalpošanas laiks būs beidzies. Populārākais pieņēmums par *CLT* kalpošanas laiku ir 50 līdz 60 gadi [31]. Turklāt *CLT* ražošanas posmu, kāds tas ir pašlaik, var uzlabot, palielinot aprites cikliskumu [35], [36].

Lai nodrošinātu efektīvu materiālu apriti, ir svarīgi labāk uzskaitīt izmantotos materiālus, atpazīt to apjomus un veidus nojaukšanas posmā, bet otrs solis ir fiziska šķirošana, atkārtota izmantošana un, ja nepieciešams, otrreizēja pārstrāde. Pētījumi liecina, ka *CLT* aprites cikla vislielākā ietekme uz vidi rodas *CLT* ražošanas posmā [36]. Lai gan būvdarbu sagatavošanas fāzē radušos atgriezumus var izmantot pārstrādātu *CLT* plātņu ražošanai, pārstrādes tehnoloģija vēl nav sasniegusi tirgu, lai nodrošinātu pietiekamu pārstrādi, *reCLT* Latvijā tiek ražots no vienģimenes dzīvojamo māju pēcražošanas atgriezumiem [37]. Tādējādi, izmantojot otrreizējās izejvielas lielākos apjomos, kopējā ietekme uz vidi varētu būt mazāka. Iepriekš veiktie pētījumi par CLT izmantošanu pēc kalpošanas laika beigām (*EoL*) liecina, ka lielākajai daļai aprites cikla ietekmes kategoriju ir mazāka negatīva materiāla otrreizējās pārstrādes ietekme salīdzinājumā ar izmantošanu enerģijas reģenerācijai [37]. Rezultāti parādīja, ka atgriezumu otrreizēja pārstrāde var būt lietderīga, lai samazinātu pašas būvniecības ietekmi uz vidi, jo atgriezumi tiek nosūtīti atpakaļ ražošanas posmā, tādējādi aizstājot neapstrādātu materiālu, kas nepieciešams *CLT* ražošanai. Iepriekš aprakstītā *CLT* pārstrādes tehnoloģijas pamatā ir izcilas kvalitātes atgriezumu pārstrāde, bet *CLT* pārstrādes nākotnei būs nepieciešamas tehnoloģijas, kas pārstrādās lietotu *CLT*. Pēc tam, kad *CLT* ir pakļauta mitruma iedarbībai, tās struktūru bojā sēnītes un higrotermiskie procesi [38]. Lai nodrošinātu materiāla kvalitāti, bojātos slāņus var nākties aizstāt ar jaunu materiālu, tāpēc ir ierosināta jauna tehnoloģija, kā rīkoties ar *CLT* plātnēm, kuru ārējie slāņi ir bojāti. Pirms pārzāģēšanas, pārgriešanas un šķērsgriešanas līdz vajadzīgajiem izmēriem ārējo slāni noņem, lai plātni tālāk izmantotu kā izejmateriālu otrreizēji pārstrādāta *CLT* (*reCLT*) ražošanai, izvairoties no ietekmes, ko rada serdes slāņa ražošana. Turklāt esošās koksnes atkritumu izmantošana palielina biogēnā oglekļa uzkrājumu ekonomikā [31], [39].

Būvmateriālu ietekme uz vidi kļūst arvien nozīmīgāka, jo uzņēmumi ir sākuši detalizētāk uzskaitīt oglekļa emisijas saskaņā ar Pasaules Biznesa padomes ilgtspējīgai attīstībai un Pasaules Resursu institūta izstrādāto SEG protokolu. Saskaņā ar 3. darbības jomu uzņēmumi ziņo par piegādātāju emisijām no iegādātajām precēm, tas ietver visus būvmateriālus, kas tiek izmantoti uzņēmējdarbībā [40]. Tas dod priekšrocības uzņēmumiem, kas var nodrošināt līdzvērtīgus produktus ar zemākām emisijām. Ir pierādīts, ka, izmantojot aprites uzņēmējdarbības modeļus (*CBM*), var samazināt koksnes izstrādājumu dzīves cikla kopējo ietekmi [36]. Ņemot vērā minēto, šā pētījuma mērķis ir novērtēt no pēc ražošanas saražotajiem CLT atgriezumiem un plātnēm ar pazeminātu kvalitāti saražota atkārtota CLT starpposma un

gala punkta ietekmi. Salīdzinot abu produktu ietekmi uz globālo sasilšanu, cilvēku toksicitāti, ūdens patēriņu, zemes izmantošanas izmaiņām un daudz ko citu, var novērtēt ieguvumus no *CLT* aprites palielināšanas Latvijā.

1.3.3. Koksnes pārstrādes blakusprodukti

CLT plātņu ražošanā veidojas otreizējie blakusprodukti – CLT atgriezumi, kuru izmantošana ir ļoti svarīgs priekšnoteikums ilgtspējības nodrošināšanai CLT plātņu ražotnēs. Kopumā atgriezumu pārstrāde sastāv no sešiem posmiem: koksnes šķelšanas, formatēšanas, piespiešanas, pirmās līmēšanas un presēšanas, otrās līmēšanas un presēšanas un iepakošanas (sk. 1.2. attēlu). Sistēmas robežas ir norādītas ar tumši zilu pārtrauktu līniju. SIA 'FORMA' sniedza datus par apstrādes un ražošanas procesu. Jāatzīmē, ka šī ražošanas sistēma ir izmēģinājums uzlabotai šķērsām līmētas koksnes atgriezumu pārstrādei.
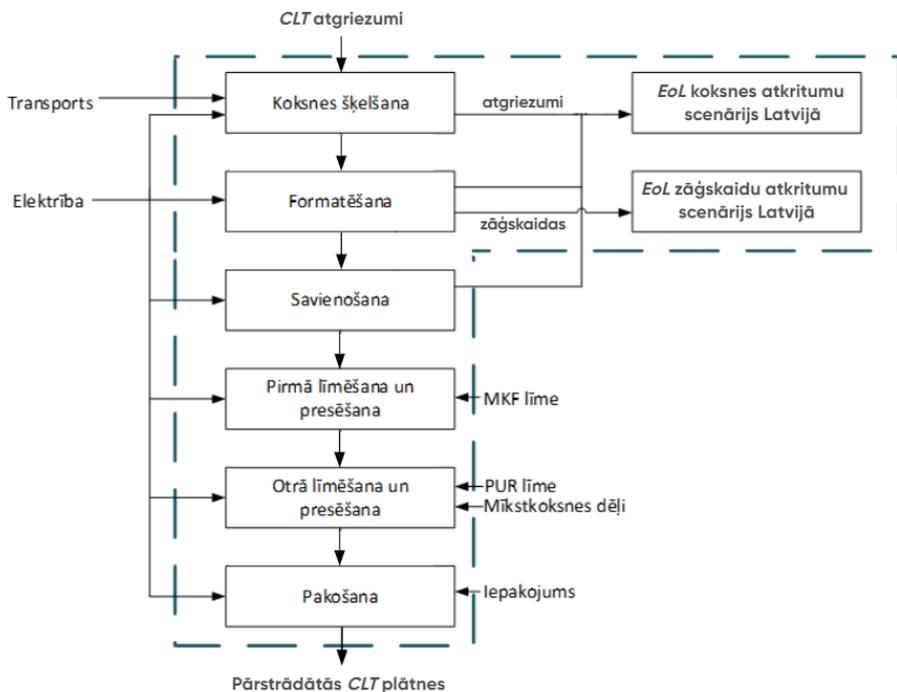
1.2. attēls. *CLT* ražošanas no *CLT* atgriezumiem plūsmas shēma ar sistēmas robežām.

CLT atgriezumi pēc ražošanas ir galvenā ienākošā plūsma. Tie ir dažāda lieluma un biezuma. Tie tiek šķiroti pēc izmantojamās platības un biezuma. Sarežģītas ģeometriskas formas tiek atdalītas, atstājot tās, kuru atkārtoti izmantojamās virsmas laukums ir lielāks par 1 m^2. Uzņēmums apstrādā 80 mm, 100 mm, 120 mm, 140 mm, 150 mm, 160 mm un 200 mm biezus *CLT* atgriezumus. Šajā analīzē 80–120 mm biezuma atgriezumi tika izslēgti, jo to pārstrādei nav nepieciešama biezuma sadalīšana, un mazāka biezuma atgriezumu pārstrāde ir

aprakstīta publikācijā [37]. Kokmateriālu atgriezumi ir iegūti no trim dažādām *CLT* ražotnēm Latvijā (*Cross Timber Systems*, *Nordic CLT*) un Igaunijā (*Arkwood*) un pārstrādāti SIA "Arkwood", Dārdu ielā 3, Ieriķos, Latvijā. Vidējais braukšanas attālums ir 163 km. Kad *CLT* atgriezumi tiek nogādāti pārstrādes vietā, visi procesi notiek vienuviet, tādējādi samazinot turpmāko transportēšanas nepieciešamību.

Atgriezumu pārstrādes process jau bija izstrādāts, to 2021. gada pētījumā aprakstīja *Vamza et al.* [37], taču uzņēmums atklāja tajā trūkumu: pārstrādātās *CLT* plātnes nav salīdzināmi ar jaunražotajiem, jo tām ir vizuāli pamanāmi savienojumi, kas samazina to izmantošanas iespējas. Lai atrisinātu šo problēmu un palielinātu biezāku atgriezumu pārstrādājamību, pārstrādes process tika pārveidots. Pārstrādes tehnoloģijas uzlabojumi ietver ārējo slāņu noņemšanu pirms *CLT* atgriezumu savienošanas un jauna slāņa uzklāšanu procesa beigās, lai nosegtu šuves. Šī pārstrādes pieeja paplašina pārstrādāto *CLT* izmantošanu, jo pēc ilgstošas ekspluatācijas slāņi var būt bojāti, tādējādi samazinot plātņu mehāniskās īpašības [108].

Jaunais pārstrādes process sākas ar ārējo slāņu noņemšanu no ienākošajiem *CLT* atgriezumiem. Noņemtie slāņi nonāk atkritumu plūsmā. Lai atdalītu slāni no pārējās CLT plātnes daļas, izmanto elektrību. Īpašais elektroenerģijas patēriņš ir 0,044 kWh uz noņemto metru. Ārējie slāņi ir 20 mm biezi. Tiek pieņemts, ka *CLT* vidējais blīvums ir 490 kg/m^3 [109].

Kad ārējie slāņi ir noņemti, *CLT* atgriezumi tiek tālāk formatēti, lai iegūtu taisnas līnijas un 90° stūrus. Formatēšanas laikā tiek noņemti 6 cm pa perimetru. Formatēšanu veic ar elektrisko zāģi, kas patērē 0,01 kWh/m elektroenerģijas. Noņemtās malas nonāk atkritumu plūsmā. Zāģējot rodas arī zāģskaidas, kas nonāk atkritumu plūsmā. Uz katru izgriezto metru tiek zaudēti 5 mm. Visi šajos procesos radušies atkritumi tiek nosūtīti kurināmā granulu ražotājiem, un šajā pētījumā tie nav iekļauti. Pilnīgā aprites ciklā šo granulu sadedzināšanas enerģiju varētu izmantot koksnes apdedzināšanas krāsnīs.

Kad ir iegūti vajadzīgie izmēri, ir jāpārliecinās, vai plātnes var savienot savā starpā. To panāk, izmantojot piespraušanas procesu, kura laikā malās tiek izgriezti pirkstu savienojumi. Šī savienojuma vizuāls attēlojums ir sniegts *Vamza et al.* pētījumā [37]. Pārstrādātās *CLT* plātnes ārējais perimetrs (18 m) paliek bez pirkstu savienojumiem. Arī šis process tiek veikts ar elektrisko zāģi, kas patērē 0,16 kWh/m. Griezuma dziļums ir 54 mm. Ņemot vērā līmlentes garumu un plātnes biezumu, tiek iegūts pirkstu savienojumu apjoms. Tāds pats tilpums tiek zaudēts zāģskaidās.

Pēc tam atgriezumus salīmē un saspiež kopā. Pārstrādatas *CLT* plātnes galīgie izmēri ir 3x6 m. Malu savienošanai izmanto melamīn-karbamīda formaldehīda (MKF) līmi. MKF līmes attiecība pret cietinātāju ir 50:50. Līmējot vienu pusi pārklāj ar MKF līmi un otru pirkstu savienojuma pusi pārklāj ar cietinātāju, tādējādi nodrošinot, ka sacietēšana notiek tikai tad, kad detaļas tiek saspiestas kopā. Līmes patēriņš ir 0,3 kg uz m^2 savienojuma virsmas. Savienojuma virsma ir 0,58 m^2/m. Pēc līmes uzklāšanas plātnes presē ar hidraulisko presi, kas patērē 0,09 kWh uz vienu presēšanu. Vidēji vienlaikus var presēt trīs gatavos izcirtņus.

Otrais līmēšanas un presēšanas posms ir jauno ārējo slāņu uzklāšana. Virsējais slānis ir izgatavots no skujkoka dēļiem, kuru izmēri ir 480 cm, 17 cm un 2 cm. Virsējā slāņa piestiprināšanai izmanto poliuretāna (PUR) līmi. Paneli pēc tam vēlreiz presē, lai iegūtu galīgo izstrādājumu. PUR līmes patēriņš ir 0,15 kg/m^2.

Pēdējais process ir gatavā produkta iepakošana. Iepakošana tiek veikta manuāli, tāpēc netiek patērēta elektroenerģija. Turklāt tiek pieņemts, ka iepakošanas procesā nerodas atkritumi, jo tiek izmantoti iepriekšējos procesa posmos iegūtie atgriezumi. Katriem 50 m³ jauna produkta (pārstrādātā *CLT*) tiek izmantots 1 m³ izgriezumu no iepriekšējiem procesiem.

1.4. Pārtikas rūpniecības bioekonomika

Bioekonomika kā starpdisciplināra un uz ilgtspējību orientēta pieeja ir kļuvusi par vienu no būtiskākajiem attīstības virzieniem pārtikas rūpniecībā. Tās mērķis ir radīt augstas pievienotās vērtības produktus un pakalpojumus, efektīvi izmantojot atjaunojamos bioloģiskos resursus un vienlaikus samazinot vides noslodzi. Literatūrā uzsvērts, ka pārtikas rūpniecības sektorā bioekonomikas koncepcijas ieviešana sniedz būtiskas iespējas gan resursu optimizācijā, gan atkritumu apjoma samazināšanā, īpaši koncentrējoties uz aprites ekonomikas principiem [171], [172].

Viens no centrālajiem aspektiem pārtikas bioekonomikā ir pārtikas atkritumu un blakusproduktu pārstrāde un izmantošana kā izejviela jaunu produktu radīšanā. Literatūras avoti apliecina, ka tādējādi iespējams iegūt biokurināmo, bioķīmiskās vielas un biopolimērus, kas var būtiski samazināt atkarību no fosilajiem resursiem [173], [174]. Turklāt bioekonomikas attīstība pārtikas sektorā tiek saistīta ar inovāciju veicināšanu, digitalizācijas risinājumu ieviešanu un jaunu, ilgtspējīgu biznesa modeļu izveidi [175].

Pētījumos arī norādīts, ka pārtikas rūpniecības bioekonomikas attīstība prasa daudzlīmeņu pārvaldības un starpnozaru sadarbības stiprināšanu. Svarīga loma ir arī patērētāju izglītošanai un iesaistei, jo pieprasījums pēc videi draudzīgiem un ētiski ražotiem produktiem būtiski ietekmē ražošanas un tirgus struktūras [176].

Kopumā literatūras analīze liecina, ka pārtikas rūpniecības transformācija bioekonomikas virzienā nav tikai tehnoloģisks vai ekonomisks jautājums – tā ir sistēmiska pieeja, kas prasa integrētu skatījumu uz vides, sociālajiem un ekonomiskajiem aspektiem. Tā ir būtiska sastāvdaļa ceļā uz ilgtspējīgu un konkurētspējīgu pārtikas sistēmu nākotnē.

Pārtikas rūpniecība ir sevišķi plaša nozares. Tā savā būtībā ir tik ļoti dažāda, ka ir izaicinoši piemeklēt kopīgus un līdzvērtīgus kritērijus tās izvērtēšanā, lai sekmētu bioekonomikas virzību, tādēļ šis pētījums piedāvā veidu, kā izvēlēties ražošanas procesus, tos uzlabot un optimizēt, kategorizēt un klasificēt atbilstoši ilgtspējības principam, analizēt ražošanas procesu uzlabošanu ar dažādām metodēm un salīdzināt tās, lai izkristalizētu labākos un piemērotākos procesus no bioekonomikas un ilgtspējības viedokļa. Pētījuma mērķis ir radīt un piedāvāt bioekonomikas iespējas, demonstrējot, analizējot un aprakstot iespējamos risinājumus ar dažādu piemēru palīdzību. Lai salīdzinātu dažādas ražošanas procesa metodes, kas palīdz saprast, kura no tām vislabāk atbilst noteiktajiem ilgtspējības kritērijiem, tika izmantota izplūdušo kognitīvo karšu (angļu val. *fuzzy cognitive maps* (*FCM*)) modelēšanas metode. Kopumā ir izvēlēti 16 dažādi ražošanas procesi, no kuriem daļa ir tieši pārtikas rūpniecības nozares ražošanas procesi, tādējādi aprobējot un pierādot, ka ar izplūdušo kognitīvo karšu modelēšanas metodi ir iespējams salīdzināt savā starpā grūti salīdzināmus, savā būtībā atšķirīgus ražošanas procesus, kuri bieži sastopami pārtikas rūpniecībā.

Labākie iespējamie risinājumi ir tādi, kuri vērsti uz esoša ražošanas procesa būtisku uzlabošanu, optimizējot to, samazinot izmešu, atlikumu un blakusproduktu daudzumu, samazinot elektroenerģijas patēriņu un virzoties uz tīrāku ražošanu, kā arī ražošanas procesu atlikumu atkārtotu izmantošanu cita produkta ražošanā. Savā starpā salīdzināti un analizēti šādi ražošanas procesi:

- citronskābes ražošana;
- sudraba nanodaļiņu sintēze;
- kompozītmateriālu ražošana;
- nanocelulozes ražošana;
- kosmētikas ražošana no piena sūkalām;
- ksilāna ražošana;
- polilaktīda ražošana;
- dabisko nātru šķiedru ražošana;
- biodīzeļdegvielas ražošana;
- Dendrolight šūnmateriāla ražošana;
- granulu ražošana;
- bioetilēna ražošana;
- celulozes ražošana;
- tanīna bāzes putu ražošana;
- skuju ekstrakta ražošana;
- lignīna ražošana.

Saskaņā ar bioekonomikas attīstības virzieniem un Eiropas Zaļā kursa pamatprincipiem šī pētījuma uzmanības centrā ir biotehnoloģisko ražošanas procesu modelēšana, izmantojot *FCM* metodi. Par piemēru kalpo citronskābes biosintēzes process, kas analizēts kā potenciāla pieeja ilgtspējīgas ražošanas attīstībai, ievērojot labāko pieejamo tehnoloģiju principus. Īpaša uzmanība pievērsta otrreizēji izmantojamu bioloģisko resursu, piemēram, augļapstrādes blakusproduktu, kā izejmateriāla izmantošanai.

Literatūras analīze apliecina, ka pāreja uz šādiem inovatīviem ražošanas modeļiem nereti prasa būtiskus ieguldījumus, detalizētu risku izvērtējumu un specifiskas zināšanas. Tomēr šāda transformācija tiek uzskatīta par loģisku un nepieciešamu soli ilgtspējīgas attīstības kontekstā.

1.5. Energoresursu atlikumi, energoefektivitāte, energopārvaldība

Energosektoram virzoties uz ilgtspējību, svarīgi ir nodrošināt augstu energoefektivitāti gan energoresursu ieguvē, gan enerģijas ražošanā, gan arī energolietotāja visās iekārtās. Lai to īstenotu, vispirms ir jāatrod spēka pielikšanas punkti un tikai pēc tam jāīsteno pasākumi. Pirmajā posmā svarīgu lomu spēlē energoaudits, ar kura palīdzību tiek definētas iespējamās enerģijas patēriņa mazināšanas vietas un pasākumi tā īstenošanai.

Energoauditi, ietverot tehniskos, ekonomiskos un vides aspektus, ir būtiski arī, lai sasniegtu ES klimata mērķus, kas paredz enerģētiskās neatkarības palielināšanu un emisiju samazināšanu par 55 % līdz 2030. gadam. Energoefektivitātes iniciatīvas cīņā pret klimata pārmaiņām,

enerģijas patēriņa samazināšanā un ilgtspējīgas attīstības veicināšanā ir ļoti būtiskas. Lai gan dalībvalstīm ir jāiegūst informācija par enerģijas patēriņu un tā potenciālajiem ietaupījumiem visaptverošā līmenī visās nozarēs, ēku īpašniekiem, komerciāliem operatoriem un pakalpojumu sniedzējiem ir jānovērtē arī savs enerģijas patēriņš un iespējamie ietaupījumi. Attiecīgi šis ir viens no energoefektivitātes un energoaudita jēdziena krustpunktiem. Energoefektivitāte nozīmē veiktspējas, pakalpojuma, preču vai enerģijas produkcijas attiecību pret enerģijas ievadi [178]. Tomēr energoauditu mērķis ir iegūt pietiekamas zināšanas par ēkas, rūpnieciskas vai komerciālas darbības, iekārtas vai privāta vai publiska pakalpojuma enerģijas patēriņu un rezultātā identificēt un kvantificēt iespējas rentablai enerģijas ietaupīšanai, identificēt rentablas atjaunojamās enerģijas izmantošanas vai ražošanas potenciālu un ziņot par konstatējumiem [178]. Respektīvi, energoauditi ir instrumenti, kas sniedz informāciju un ieteikumus uzņēmumu īpašniekiem, apsaimniekošanas uzņēmumiem, māju īpašniekiem, investoriem, dažādām finanšu iestādēm un citām attiecīgajām pusēm par ēku enerģijas patēriņu un stāvokli, iespējamiem tehniskiem uzlabojumiem un līdz ar to enerģijas patēriņa samazināšanu [184]. Izmantojot enerģiju efektīvāk un tādējādi patērējot mazāk, visi ES valstu iedzīvotāji un uzņēmumu īpašnieki var samazināt savus enerģijas rēķinus, palīdzēt aizsargāt vidi, mazināt klimata pārmaiņas, uzlabot dzīves kvalitāti, samazināt ES atkarību no importētiem naftas un dabasgāzes piegādātājiem, atbalstīt ilgtspējīgu izaugsmi un veicināt ES un citu valstu ekonomiku [182]. Lai sasniegtu šos ieguvumus, energoefektivitāte ir jāuzlabo gan piedāvājuma, gan pieprasījuma pusē, sākot no ražošanas līdz galapatēriņam [179], [180]. Lai virzītos uz Zaļā kursa mērķiem un ievērotu direktīvu prasības, daudzas valdības ir izveidojušas un īstenojušas dažādas iniciatīvas, noteikumus un plānus, kas paredz energoefektivitāti veicinošus pasākumus un politiku, īpašu uzmanību pievēršot enerģijas pārvaldības sistēmu ieviešanai un energoauditu veikšanai, jo tie ir noderīgi instrumenti energoefektivitātes palielināšanai [183], [184].

2. IZPĒTES METODES

2.1. Daudzkritēriju lēmumu pieņemšanas metode (*MCDA*)

Daudzkritēriju lēmumu pieņemšanas metode (*MCDA*) ir izplatīta metode lēmumu pieņemšanas problēmu risināšanai. Tā ir piemērota jebkurai jomai, kurā var definēt problēmu, kritērijus un alternatīvas, kas jāsalīdzina [11]. Šī darba ietvaros tā lietota gan tekstila aprites potenciāla izvērtējumam, gan jauktā tekstila atkritumu pārstrādes izvērtējumam.

Promocijas darbā izmantotais TOPSIS analīzes modelis

Lai uzsāktu daudzkritēriju lēmumu pieņemšanas metodes aprēķinus, viens no posmiem ir kritērijiem piešķirt svarīguma koeficientu, kas norāda katra kritērija nozīmīgumu. Kritēriju svarīgumu var noteikt ar dažādām metodēm, piemēram, analītiskās hierarhijas procesu [18] vai jutīguma analīzi [17]. Šajā gadījumā, ņemot vērā, ka analizējamo kritēriju skaits pārsniedz septiņus, analītiskās hierarhijas metodi izmantot nav iespējams, jo iegūtie rezultāti būtu nekonsekventi [18]. Tāpēc šajā pētījumā pieņemts, ka visiem kritērijiem ir vienāda nozīme, t. i., visiem tika piešķirts vienāds svarīguma koeficients.

Pēc ievaddatu un svarīguma koeficientu noteikšanas analīzei lietota *TOPSIS* metode. Tā sastāv no pieciem posmiem [18].

1. Lēmumu matricas normalizācija:

$$R = \frac{X}{\sqrt{\sum X^2}} \, , \qquad (2.1.)$$

kur R ir normalizētā matricas vērtība un X ir kritērija vērtība.

2. Svaru lietošana lēmumu matricai:

$$V = R \cdot W \, , \qquad (2.2.)$$

kur V ir svērtā vērtība un W ir kritērija svarīguma koeficients.

3. Ideālā un antiideālā vērtību noteikšana:

kur V^+ ir maksimālā svērtā vērtība, V^- – minimālā.

4. Attāluma aprēķināšana līdz ideālajām un antiideālajām vērtībām:

$$d_{\mathrm{a}}^+ = \sqrt{\sum \left(V^+ - V \right)^2} \, , \qquad (2.4.)$$

kur d_{a}^+ ir attālums līdz ideālajam risinājumam.

$$d_{\mathrm{a}}^{-} = \sqrt{\Sigma \left(V^{-} - V \right)^{2}} \ , \tag{2.5.}$$

kur d_{a}^{-} ir attālums līdz antiideālajam risinājumam.

5. Relatīvā tuvuma aprēķins:

$$C_{\mathrm{a}} = \frac{d_{\mathrm{a}}^{-}}{d_{\mathrm{a}}^{+} - d_{\mathrm{a}}^{-}} \ , \tag{2.6.}$$

kur C_{a} ir relatīvā tuvība ideālajam risinājumam. Vislabāko alternatīvu nosaka, salīdzinot to relatīvo tuvību ideālajam risinājumam.

Jutīguma analīze

Jutīguma analīze tiek veikta, lai novērtētu kritēriju ietekmi uz gala rezultātiem un apstiprinātu to ticamību. Jutīguma analīzei ir vairāki posmi [23].

Sākotnēji pieņem, ka visiem kritērijiem ir vienāds svarīgums:

$$w' = \frac{1}{n} \ , \tag{2.7.}$$

kur w' ir sākotnējais svarīguma koeficients un n – kritēriju skaits.

Tad viena kritērija svarīgums tiek mainīts atbilstoši vienības variācijas koeficientam:

$$w'_{k} = \beta_{km} \cdot w',' \tag{2.8.}$$

kur:
w'_{k} – maināmais svarīguma koeficients;
β_{km} – vienības variācijas koeficients;
$k = 1, 2, 3\ldots n$;
$m = 1, 2, 3\ldots n$.

Pārējo kritēriju svarīguma koeficientus aprēķina pēc šādas formulas:

$$w'_{km} = \frac{\left(1 - w'_{k} \right)}{\left(n - 1 \right)} . \tag{2.9.}$$

Darbā veikta jutīguma analīze ar pieciem vienības variācijas koeficientiem (β_{k} = 0,01; 0.5; 1,5; 2; 2,5). Pārbaudīti arī lielāki koeficienti, piemēram, 3 un 4, taču kritēriji jau pietiekami reaģēja uz izmaiņām, tādēļ saglabāti sākotnējie koeficienti. Koeficientu vērtības palielinātas pa 0,5 soļiem, kas nozīmē, ka ar katru nākamo soli attiecīgā kritērija ietekme (svarīgums) proporcionāli palielinās. Rezultātā iegūtie svarīguma koeficienti izmantoti *TOPSIS* aprēķinos, lai iegūtu jutīguma analīzes rezultātus. Šī procedūra veikta visiem kritērijiem.

2.1.1. Daudzkritēriju lēmumu pieņemšanas metode tekstila aprites potenciālam

Kritēriju izvēle

MCDA analīze sākas ar kritēriju atlasi. Kritēriji izvēlēti, pamatojoties uz to atbilstību pētījuma mērķim un pieejamajiem datiem. Lai novērtētu aprites ekonomikas attīstības iespējas tekstilizstrādājumu grupām [75], kritēriji pārstāv četras kategorijas: vides, ekonomiskos, sociālos un tehniskos aspektus. Izvēlētie piecpadsmit kritēriji ir parādīti 2.1. tabulā. Tehniskais aspekts tika iekļauts, lai analīze būtu daudzveidīgāka un vairāk saistīta ar aprites ekonomikas attīstību.

2.1. tabula.

Daudzkritēriju lēmumu analīzes kritēriji

Kritēriju kategorija	Kritēriji	Ideālā vērtība
Vides aspekti	Ietekme uz vidi – produkta globālās sasilšanas potenciāls, $kgCO_2eq\ kg^{-1}$.	+
	Mazgāšanas reizes – lietošanas ietekme uz vidi, ko nosaka pēc tekstilizstrādājuma mazgāšanas reizēm vidēji.	+
	Paredzamais kalpošanas laiks – vidējais produkta kalpošanas laiks gados.	–
	Poligonā apglabāto atkritumi – poligonā apglabāto atkritumu attiecība pret kopējo atkritumu daudzumu, %.	+
	Pārstrādātie atkritumi – pārstrādāto atkritumu īpatsvars no kopējā atkritumu daudzuma, %.	–
	Auduma izcelsme - sintētisko materiālu attiecība, %.	+
Ekonomiskie aspekti	Tirgus pieprasījums – pasaules tirgus apjoma novērtējums, miljardi EUR.	+
	Ražošanas apjoms – saražotā produkta apjoma attiecība, %.	+
	Starptautiskā tirdzniecība – eksportētās produkcijas apjoma attiecība, %.	+
	Darba ražīgums – bruto pievienotā vērtība uz vienu nodarbināto, tūkst. EUR.	+
	Pievienotā vērtība – pievienotās vērtības īpatsvars kopējā ražošanā, %.	+
Tehniskie aspekti	Ražošanas tehnoloģiju energoefektivitāte – enerģijas patēriņa attiecība produktu ražošanas posmā pret enerģijas patēriņu visā dzīves ciklā, %.	+
	Inovācijas kapacitāte – patentu skaits, kas iesniegti no 2015. līdz 2019. gadam, patenti.	+
Sociālie aspekti	Nodarbinātība – nozarē nodarbināto personu īpatsvars, %.	+
	Uzņēmumi – nozares uzņēmumu īpatsvars, %.	+

Ideālā vērtība attēlota kā "+" vai "–". Ja ideālā vērtība ir maksimālā vērtība, tad kritēriji tiek attēloti ar plusa simbolu, bet, ja ideālā vērtība ir minimālā vērtība, tad ir pretējs simbols. Šajā gadījumā tekstilmateriālu aprites potenciāla analīzes publikācijas [75] mērķis bija atrast, kurā grupā ir vislielākās iespējas aprites ekonomikas attīstībai, nevis kurā nozarē jau ir visaugstākā aprites efektivitāte. Vides un tehnisko aspektu ideālās vērtības ir pretrunā. Piemēram, augstāka ietekme uz vidi tiek definēta kā ideālais gadījums, jo, ja tekstilizstrādājumu grupai ir augsta ietekme uz vidi, tā, visticamāk, nav veikusi ilgtspējības uzlabošanas pasākumus, piemēram, aprites ekonomikas pasākumus, tāpēc šajā nozarē ir daudz iespēju aprites ekonomikas attīstībai. Vēl viens piemērs ir pārstrādātie atkritumi. Jo mazāk atkritumu kādā nozarē tiek pārstrādāts, jo vairāk tos var pārstrādāt, tāpēc ir lielākas iespējas attīstīt aprites ekonomiku.

Vides aspekti

Piemērā par tekstilmateriālu aprites potenciālu [75] ietekme uz vidi tika noteikta pēc aprites cikla novērtējuma (ACN) pētījumiem. Nav ACN pētījumu, kuros tiktu pētīta visa tekstilizstrādājumu grupa. Tāpēc, novērtējot šo rādītāju, tika ņemts vērā katras plūsmas tekstilizstrādājumu ACN. Izstrādājuma globālās sasilšanas potenciāls (GSP) bija kvantitatīvais rādītājs, ko izmantoja turpmākajā analīzē.

Lai novērtētu tekstilizstrādājumu lietošanas dzīves posmu, tika ieviests mazgāšanas laika kritērijs. Aptuveni 14 % no tekstilizstrādājumu ietekmes uz klimata pārmaiņām ir lietošanas posmā, jo ievērojams ūdens un enerģijas patēriņš rodas materiālu mazgāšanas un žāvēšanas laikā [65]. Arī šajā aprites cikla posmā jūras vidē veidojas piesārņojums ar ķīmiskām vielām un mikroplastmasu [67]. Tādējādi šis kritērijs tiek izmantots, lai novērtētu ietekmi uz vidi.

Otrs izvēlētais lietošanas posma kritērijs bija paredzamais kalpošanas laiks. Tā kā mazgāšanas biežums ir atkarīgs no tekstilizstrādājuma, mazgāšanas rādītājs nevar pilnībā raksturot tā kalpošanas laiku. Piemēram, T-krekls tiek mazgāts bieži, bet tam ir īss kalpošanas laiks [83], [84], kas norāda, ka liels mazgāšanas gadījumu skaits izstrādājuma kalpošanas laikā ne vienmēr norāda, ka izstrādājumam ir ilgs kalpošanas laiks. Kalpošanas laiks lielā mērā ir atkarīgs no tekstilizstrādājuma kvalitātes un lietotāja [69]. Tekstilizstrādājuma kalpošanas laiks ir svarīgs ietekmes uz vidi rādītājs. Jo ilgāk tekstilizstrādājums tiek lietots, jo mazāka ir tā ietekme uz vidi. Piemēram, tiek lēsts, ka ietekme uz vidi samazinātos par 20 % līdz 30 %, ja apģērba kalpošanas laiks būtu deviņus mēnešus ilgāks [85].

Lai novērtētu ietekmi uz vidi pēc ekspluatācijas beigām, tika pievienoti divi kritēriji: poligonos apglabātie atkritumi un pārstrādātie atkritumi. Tekstilizstrādājumi pēc lietošanas posma visbiežāk nonāk atkritumu poligonā vai tiek sadedzināti [2]. Ja tekstilizstrādājumi tiek šķiroti, tie lielākoties tiek pārstrādāti vai atkārtoti izmantoti. Ir pieejami dati par tekstilizstrādājumu atkritumu apsaimniekošanu visā pasaulē, taču tie nav sadalīti pa tekstilizstrādājumu plūsmām. Pasaulē aptuveni 73 % apģērbu pēc lietošanas tiek apglabāti poligonos vai sadedzināti [2]. Ir būtiski atzīmēt, ka lielākajā daļā ACN pētījumu tiek pieņemts, ka visiem tekstilizstrādājumiem aprites cikla beigu posms ir vienāds, taču patiesībā, pat ja izstrādājums ir izgatavots no viena un tā paša šķiedras veida, ietekme uz vidi ir atšķirīga [3].

Būtisks faktors tekstilizstrādājuma ietekmes uz vidi novērtējumā ir izmantotā materiāla veids [86]. Tā kā šajā pētījumā ietvertas tekstilizstrādājumu plūsmas, nevis konkrēti

izstrādājumi, tika aplūkotas divas galvenās materiālu kategorijas: sintētiskās un dabiskās šķiedras. Sintētisko materiālu attiecība parāda, cik daudz katrā grupā tiek izmantoti neatjaunojamie resursi.

Ekonomiskie aspekti

Lai novērtētu ekonomiskās izaugsmes iespējas, tika izmantots tirgus pieprasījums. Tirgus apjoms norāda aprites ekonomikas attīstības rentabilitāti. Tika izveidots ražošanas kritērijs, lai labāk izprastu tekstilizstrādājumu tirgus sadalījumu. Kopējās tekstilizstrādājumu produkcijas sadalījums pa nozarēm norāda tekstilizstrādājumu plūsmu lielumu. Jo lielāki ir ražošanas apjomi, jo lielākas ir ekonomiskās attīstības iespējas. Dati par ražošanas sadalījumu pasaulē nav pieejami, tāpēc tika ņemti dati par ES.

Eksports veicina katras valsts ekonomisko izaugsmi. Taču, tā kā šajā pētījumā aplūkots pasaules mērogs, šis rādītājs tika izveidots, lai atspoguļotu starptautisko tirdzniecību tekstilizstrādājumu sistēmās. Vides piesārņojums rodas izplatīšanas posmā, bet, tā kā šis kritērijs tiek aplūkots ekonomiskajā aspektā, jo lielāks ir eksportēto produktu īpatsvars, jo aktīvāka šajā produktu plūsmā ir starptautiskā tirdzniecība.

Pievienotā vērtība norāda katras tekstilizstrādājumu grupas ekonomisko nozīmi. Lai to novērtētu, tika noteikti divi kritēriji: darba ražīgums un pievienotā vērtība. Pirmais kritērijs parāda bruto pievienoto vērtību uz vienu nodarbināto. Jo lielāka pievienotā vērtība uz vienu nodarbināto, jo efektīvāka ir nozare. Otrais kritērijs rāda pievienotās vērtības īpatsvaru kopējā produkcijā, kas norāda katras tekstilrūpniecības nozares ekonomisko nozīmi kopējā ražošanas nozarē.

Tehniskie aspekti

Lai šajā pētījumā iekļautu tehnisko aspektu, tika novērtēā ražošanas tehnoloģiju energoefektivitāte. Tika izmantoti dati par tekstilizstrādājumiem katrai grupai atsevišķi, jo nav veikti pētījumi par kopējo ainu. Tika novērtēta tehnoloģiju efektivitāte ražošanas posmā un tāpēc izmantota attiecība starp enerģijas patēriņu izstrādājumu ražošanas posmā un enerģijas patēriņu visā aprites ciklā. Jo lielāks ir enerģijas patēriņa procentuālais īpatsvars, jo neefektīvākas ir ražošanas tehnoloģijas.

Lai novērtētu katras nozares tehnoloģisko attīstību, tika pārbaudīta inovācijas spēja. Tekstilrūpniecībā regulāri tiek ieviestas inovācijas jaunu materiālu, lietojumu, risinājumu un produktu veidā. Inovācijas spēju var novērtēt pēc patentiem, dizainparaugiem, preču zīmēm un uzņēmumu pētniecības un attīstības izdevumiem [87]. Šajā gadījumā inovācijas kapacitāti noteikta pēc patentu skaita. Vairāk patentu nozīmē lielāku inovācijas spēju.

Sociālie aspekti

Sociālais aspekts ir ietekmīga sastāvdaļa pārejā uz aprites ekonomiku, tāpēc šajā pētījumā tika iekļauts arī sociālais aspekts. Mērķis bija novērtēt nodarbinātību katrā tekstilizstrādājumu grupā, tāpēc kā rādītāji tika ņemta nodarbinātība un uzņēmumi. Nodarbinātība norāda uz pašreizējo situāciju, savukārt uzņēmumu skaits iezīmē nākotnes iespējas. Lielāks uzņēmumu

skaits nozīmē lielākas un daudzveidīgākas darba iespējas nozarē. Jo vairāk uzņēmumu, jo lielāka iespēja, ka tiks radītas jaunas darba vietas.

MCDA

Iepriekš tika apskatīti aspekti tekstilmateriālu aprites potenciāla noteikšanai un to raksturojošie kritēriji. Datu analīzei izmantota *TOPSIS* metode un minētajā tekstilmateriālu aprites potenciāla piemēra gadījumā visi dati ir kvantitatīvi, bet šajā metodē var izmantot arī kvalitatīvus datus [11]. Rezultāts ir alternatīvu attālums līdz ideālajam punktam. Ideālais punkts šajā metodē ir vērtība viens, kas nozīmē, ka alternatīva, kuras vērtība ir vistuvāk vienam, ir vislabākā [11]. *TOPSIS* aprēķiniem izmantots *MS Excel. MCDA* ir trīs posmi [88].

1. Ieejas datu definēšana – visi aprēķini ir balstīti uz ieejas datiem un izvēlētajām alternatīvām un kritērijiem. 2. tabulā ir norādīti piecpadsmit kritēriji, un alternatīvas ir trīs galvenās tekstilizstrādājumu grupas: modes, mājas un tehniskais tekstils.

2. Kritēriju svarīgums– kritērijiem tiek piešķirti dažādi svari, lai salīdzinātu kritēriju nozīmi. Svarus var noteikt, izmantojot analītiskās hierarhijas procesu (AHP) un jutīguma analīzi. Tā kā ir vairāk nekā septiņi kritēriji, rezultāti, izmantojot AHP, būtu pretrunīgi [11]. Tāpēc jutīguma analīze tika izmantota piemērā par tekstilmateriālu aprites potenciālu ar pieciem vienādiem variāciju koeficientiem (0,01; 0,5; 2; 3; 4). Analīzes soļi ir izskaidroti *Peiyue Li et al.* pētījumā [89]. Kritēriji tika iedalīti trīs grupās, pamatojoties uz jutīguma analīzes rezultātiem: augsta, vidēja un zema jutība. Kritēriju sadalījumu pa grupām noteica pēc vidējās starpības starp augstāko un zemāko alternatīvu relatīvā tuvuma ideālajam risinājumam. Šo vidējo vērtību sauc par jutīguma rādītāju. Ja jutīguma rādītājs bija mazāks par 0,1, tad tā jutīgums tika uzskatīts par zemu; ja tas bija lielāks par 0,2, tad tas tika uzskatīts par augstu; un ja tas bija no 0,1 līdz 0,2 ieskaitot, tad kritērija jutīgums bija vidējs. Augstas jutības kritērija svaru ieguva, reizinot sākotnējo svaru ar 1,5, bet zemas jutības kritērija svaru ieguva, reizinot ar 0,5. Vidējas jutības kritērija svaru aprēķināja, dalot atlikušo svaru ar kritēriju skaitu. Iegūtie svarīguma rādītāji tika saskaņoti ar nozares ekspertiem, lai pārliecinātos, ka svērumu sadalījums ir pareizs.

3. TOPSIS aprēķini – tika izmantoti pieci aprēķinu soļi, pamatojoties uz Zlaugotne B. *et al.* [11] pētījumu.

2.1.2. Daudzkritēriju lēmumu pieņemšanas metode jauktā tektstila atkritumu pārstrādei

Daudzkritēriju lēmumu pieņemšanas metode ir pietiekami universāla un ar plašu lietojumu loku. Pētījumā [Analysis of Textile Circularity Potential] daudzkritēriju lēmumu pieņemšanas metode tika lietota modes tekstila aprites potenciāla izvērtēšanai, savukārt nākamajā pētījumā [Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development] daudzkritērjiju lēmumu pieņemšanas metode tiek lietota ar citiem uzsvariem, fokusējoties uz jaukta tekstila atkritumu pārstrādes procesu izvērtējumu. Tā ir piemērojama jebkurā jomā, kur iespējams formulēt problēmu, noteikt kritērijus un salīdzināmas alternatīvas [18]. Pastāv vairākas *MCDA* metodes, taču katrai no tām ir savas aprēķinu darbības, tāpēc rezultāti var atšķirties pat tad, ja ievaddati ir identiski.

Šajā pētījumā tika izvēlēta metode "Tehnika izvēles secības noteikšanai pēc līdzības ar ideālu risinājumu" (angļu val. *Technique for Order Preference by Similarity to Ideal Solution – TOPSIS*), pamatojoties uz autores iepriekšējo pētījumu, kurā tika veikta produktu salīdzināšana [17], kas ir arī šī pētījuma mērķis. *TOPSIS* metode piedāvā salīdzinoši vienkāršus aprēķinu soļus, ļauj izmantot neierobežotu kritēriju un alternatīvu skaitu, un ievaddati var būt gan kvalitatīvi, gan kvantitatīvi [18]. Rezultātā iegūtais vērtējums atspoguļo attālumu no alternatīvas līdz ideālajam punktam, kas šajā metodē ir vienāds ar viens. Jo tuvāk vērtējums ir skaitlim viens, jo piemērotāka ir alternatīva. *TOPSIS* aprēķini tika veikti, izmantojot *MS Excel* programmatūru.

MCDA analīze tika veikta, sekojot autores iepriekšējā pētījumā izstrādātajiem soļiem [17]:
1) produkta identificēšana. Pirmais solis bija literatūras analīze, lai identificētu produktus;
2) kritēriju izvēle un datu vākšana. Šajā posmā tika atlasīti kritēriji un savākti ievaddati;
3) *TOPSIS* analīze. Šajā posmā tika veikti aprēķini un iegūti gala rezultāti;
4) jutīguma analīze. Noslēdzošais solis bija rezultātu pārbaude, izmantojot jutīguma analīzi.

Produkta identificēšana

Literatūras analīzes mērķis bija identificēt produktus, ko iespējams iegūt no jauktiem tekstilmateriāliem pēc lietošanas. Tika izmantotas trīs zinātniskās datubāzes: *Scopus*, *Science Direct* un *Web of Science*. Visās datubāzēs tika lietota atslēgvārdu kombinācija "*post-consumer mixed textile recycling*". Tā kā *Web of Science* datubāzē tika atrasts nepietiekams rakstu skaits (33 rezultāti), atslēgvārdi tika nomainīti uz "*textile waste recycling products*". Kopumā pēc šiem atslēgvārdiem tika atrasts ievērojams skaits publikāciju: *Science Direct* – 2678 rezultāti, *Scopus* – 944 un *Web of Science* – 799. Tika atlasīts saturs angļu valodā, kas nav vecāks par desmit gadiem (no 2014. gada). Katras datubāzes pirmie 100 ieraksti tika pārskatīti, sakārtoti pēc atbilstības. Turpmākajam pētījumam ieraksti tika atlasīti pēc virsraksta un anotācijas.

Lai izvēlētos rakstus pēc diviem kritērijiem (izmantoti tekstilizstrādājumi pēc lietošanas un tie ir jaukti tekstilmateriāli), bija nepieciešama papildu kvalitatīvā analīze. Visi produkti tika izvērtēti atbilstoši šiem diviem kritērijiem. Mērķis bija identificēt produktus, kas atbilst abiem nosacījumiem.

Kritēriju izvēle un datu vākšana

Visi aprēķini tika balstīti uz ievaddatiem, izvēlētajām alternatīvām un noteiktajiem kritērijiem. Turpmākai alternatīvu analīzei tika izvēlēti produkti un produktu komplekti, kas iegūti no jauktiem tekstilatkritumiem pēc lietošanas. Produkti tika kategorizēti, balstoties uz pētnieciskajiem rakstiem. Piemēram, pētījumā, ko veica Andini u. c. [19], tika iegūti četri galvenie produkti, taču tie netika vērtēti atsevišķi, jo visi tika iegūti vienā ražošanas ciklā, izmantojot to pašu izejmateriālu.

Pēc salīdzināmo alternatīvu noteikšanas nākamais solis bija kritēriju izvēle. Kritēriji tika izvēlēti, pamatojoties uz to atbilstību pētījuma mērķim un pieejamajiem datiem. Lai novērtētu produktu attīstības potenciālu, kritēriji tika iedalīti četrās kategorijās: vides, ekonomiskie,

sociālie un tehniskie aspekti. Šīs kategorijas tika izvēlētas tādēļ, ka tehniskie parametri ir būtiski tehnoloģijas izvērtēšanā, bet ilgtspējas aspekti – attīstības novērtēšanā [20]. Izvēlētie deviņi kritēriji ir parādīti 2.2. tabulā. Visos gadījumos ideālā vērtība ir maksimālā, proti, jo augstāka vērtība, jo labāka alternatīva.

2.2. tabula.

Daudzkritēriju lēmumu analīzes kritēriji

Kritēriju kategorija	Kritērijs	Apraksts
Vides aspekti	Vides ietekme	Globālās sasilšanas potenciāla salīdzinājums jaunajam un traicionālajam produktam (reizes)
	Resursu efektivitāte	Citu atkritummateriālu izmantošana ražošanā (svara īpatsvars, %)
	Ilgmūžība un pārstrāde	Produkta kalpošanas ilgums un tā pārstrādes potenciāls (punktu vērtējums)
Ekonomiskie aspekti	Produkta cena	Jaunā un tradicionālā produkta cenas salīdzinājums (reizes)
	Tirgus pieprasījums	Globālā tirgus apjoma novērtējums (miljardi EUR)
Tehniskie aspekti	Tehnoloģiju gatavības līmenis	Tehnoloģiskās gatavības līmenis (*TRL* 1–9)
	Izpētes līmenis	Pētījumu skaits par līdzīgiem produktiem (punktu vērtējums)
	Tirgus konkurētspēja	Jaunā un tradicionālā produkta īpašību salīdzinājums (punktu vērtējums)
Sociālie aspekti	Sociālie aspekti	Drošības un veselības risku novērtējums ražošanas laikā un darba rakstura specifika (punktu vērtējums)

Vides aspekti

Vides ietekme tika noteikta, pamatojoties uz dzīves cikla novērtējuma (*Life Cycle Assessment*, *LCA*) pētījumiem. Tā kā analizētie produkti ir inovatīvi, tiem *LCA* pētījumi vēl nav veikti, tādēļ tika atlasīti līdzīgi produkti, kuriem jau ir veikti *LCA* pētījumi. Kā kvantitatīvais indikators tika izmantots globālās sasilšanas potenciāls (*Global Warming Potential*, *GWP*), kas ir plaši lietots rādītājs vides ietekmes komunikācijā [21]. Ja pētījumā jau bija pieejami dati par tradicionālajiem produktiem, tie tika izmantoti salīdzinājumam. Ja šādu datu nebija, tie tika iegūti no *Ecoinvent 3.10* datubāzes, izmantojot to pašu metodi, kas tika lietota salīdzinošajā pētījumā. Esošā produkta vērtība tika dalīta ar jaunā produkta vērtību, lai iegūtu, cik reizes iespējams samazināt vides ietekmi. Ja šī vērtība ir mazāka par vienu, tas nozīmē, ka jaunā produkta vides ietekme pēc *GWP* ir lielāka.

Lai novērtētu aprites ekonomikas potenciālu, tika iekļauts kritērijs "Resursu efektivitāte". Izvēlētie produkti jau veicina aprites ekonomiku, jo to izejmateriāls ir tekstila atkritumi, tāpēc šis kritērijs ļauj analizēt, vai ražošanas procesā tiek izmantoti arī citi blakusprodukti vai

atkritumi, kas vēl vairāk palielinātu ieguldījumu apritē. Rādītājs tiek noteikts kā attiecība pret galaprodukta svaru. Ja netiek izmantoti citi blakusprodukti, alternatīva saņem vērtējumu nulle.

Pirmie divi kritēriji attiecas uz ražošanas fāzi, savukārt kritērijs "Ilgmūžība un pārstrādājamība" ieviests, lai novērtētu arī lietošanas posmu un produkta dzīves cikla beigas. Šis kritērijs ietver gan produkta kalpošanas ilguma, gan pārstrādājamības novērtējumu. Abi aspekti vērtēti trīspunktu skalā. Pārstrādes vērtēšanas skala: (1) nav pārstrādājams vai parasti netiek pārstrādāts, (2) pārstrādāts zemākas kvalitātes produktos vai ir bioloģiski noārdāms, (3) pārstrādāts slēgtā ciklā. Kalpošanas ilguma vērtēšanas skala: (1) vienreizējs lietojums, (2) izmantojams līdz 10 gadiem, (3) izmantojams ilgāk par 10 gadiem. Abus vērtējumus sareizinot, iegūst maksimālo rezultātu – 9 punktus.

Ekonomiskie aspekti

Produkta cena ir būtisks indikators, lai noteiktu tā ekonomisko dzīvotspēju un konkurētspēju. Cena ir konkrēts rādītājs (cena uz produkta vienību) atšķirībā no citiem ekonomiskajiem indikatoriem, kurus ir grūtāk salīdzināt, piemēram, sākotnējās investīcijas, kas lielā mērā ir atkarīgas no ražošanas apjoma. Tāpat kā *LCA* pētījumos, arī šeit inovatīviem produktiem bieži vien ekonomiskais novērtējums nav veikts, tādēļ tie salīdzināti ar līdzīgiem tradicionālajiem produktiem. Arī tradicionālā produkta cena noteikta salīdzināšanai. Esošā produkta vērtība tika dalīta ar jaunā produkta cenu, lai aprēķinātu, cik reizes jaunais produkts ir lētāks. Ja rezultāts ir mazāks par 1, tas nozīmē, ka jaunā produkta cena ir augstāka un šobrīd tas nav ekonomiski pamatots. Otrs ekonomiskais aspekts ir vērsts uz pieprasījumu. Globālā tirgus apjoms izmantots, lai noteiktu, vai produkts ir pieprasīts. Jo lielāks tirgus novērtējums, jo augstāks pieprasījums pēc attiecīgā produkta.

Tehniskie aspekti

Tehnoloģiskās gatavības līmenis (*Technology Readiness Level*, *TRL*) izmantots, lai novērtētu, cik attīstītas un mērogojamas ir pētījumā izstrādātās tehnoloģijas. *TRL* ir atzīta kā efektīva metode jaunu tehnoloģiju attīstības posmu komunikācijai dažādās nozarēs [22]. Novērtēšana veikta pēc deviņu punktu skalas. Lai nodrošinātu padziļinātu izpratni un vērtējumu, izmantots J. Mankinsa *TRL* apraksts [22].

Lai novērtētu produkta izpētes līmeni, ieviests kritērijs "Izpētes līmenis", kas ļauj analizēt publikāciju skaitu par attiecīgo tēmu. Šī kritērija izvērtēšanai izmantota *Scopus* datubāze. Katras alternatīvas atslēgvārdu pamatā ir produkta tips, izmantotā metode, un tie ietvēra terminu "*textile*". Atrastās publikācijas kvalitatīvi analizētas, izskatot to anotācijas un nosaukumus. Tālākai izvērtēšanai atlasītas tikai tās publikācijas, kurās bija minēts līdzīgs produkts un izmantoti tekstilmateriāli.

Pirmajai alternatīvai izmantoti atslēgvārdi "*textile hydrothermal liquefication*". Atrastas 13 publikācijas. Otrajai alternatīvai izmantoti atslēgvārdi "*textile reinforced composites building*". Šādi atrastas 138 publikācijas. Šajā gadījumā pievienots papildinājums "*AND NOT*" ar vārdiem "*concrete*" un "*cement*", lai izslēgtu analīzei neatbilstošos rakstus. Trešās alternatīvas meklējumos izmantoti atslēgvārdi "*microwave assisted glycolysis textile*", atrodot divus

rezultātus. Ceturto alternatīvu analizējot, izmantoti atslēgvārdi "*mycelium composite textile*", atrodot 35 rezultātus.

Kritērijs "Tirgus konkurētspēja" iekļauts, lai izvērtētu produkta tehniskās īpašības. Analizētas izvēlēto alternatīvu īpašības, kādas tās norādītas attiecīgajos pētījumos, un salīdzinātas ar tradicionālo produktu raksturlielumiem. Ja salīdzinājums jau bija veikts aplūkotajā pētījumā, izmantoti tajā ietvertie dati. Tradicionālā produkta raksturlielumi noteikti papildus. Lai gan atšķirības var izteiktas procentos vai līdzīgos rādītājos, šie dati nav tieši salīdzināmi starp dažādām produktu grupām. Dažās nozarēs nelielas atšķirības ir nenozīmīgas, bet citās – ļoti būtiskas, tādēļ raksturlielumi novērtēti punktos. Vērtēšanas sistēma: (1) īpašības sliktākas nekā tirgus produktiem, (2) īpašības līdzīgas, (3) uzlabotas īpašības.

Sociālie aspekti

Sociālie aspekti vērtēti ar punktiem. Ņemti vērā divi aspekti: darba specifika un drošība ražošanas procesā. Darba specifika izvērtēta pēc nepieciešamā darbaspēka kvalifikācijas un zināšanu līmeņa, lai analizētu iespējamo ietekmi uz darba tirgu. Ja produkta ražošanā nepieciešams darbaspēks ar dažādu prasmju un izglītības līmeni, tas pozitīvi ietekmē darba tirgu. Vērtēšanas sistēma: (1) augsti specializēti darbi, (2) specializēti darbi, (3) darbi ar dažādiem prasmju līmeņiem. Ņemti vērā arī darba drošības un veselības riski. Šis aspekts vērtēts pēc šādas sistēmas: (1) augsta riska darbs, (2) vidēja riska darbs, (3) minimāla riska darbs. Abi vērtējumi sareizināti, iegūstot maksimālo iespējamo punktu skaitu – 9.

2.1.3. Daudzkritēriju lēmumu pieņemšanas metode CO_2 uzglabāšanai mežizstrādes atlikumos

Pētījumam izvēlēta cieto koka plātņu izolācijas materiāla ražošana. Ražošanas metodoloģija sastāv no tādiem posmiem kā ražošanas procesa apraksts un nepieciešamās izejvielas, kas ļauj aprēķināt CO_2 daudzumu, ko var uzkrāt galaproduktā. Enerģijas avoti cieto plātņu ražošanā, izmantojot daudzkritēriju analīzes metodi, arī tika salīdzināti trīs dažādos scenārijos. Visi metodoloģijas posmi ir redzami 2.1. attēlā.
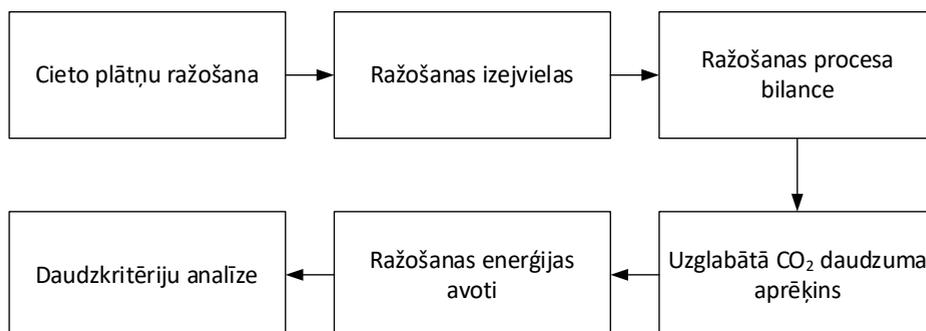
2.1. att. Metodoloģijas algoritms.

Cieto plātni ražo līdzīgi kā citas kokšķiedras plātnes, piemēram, *MDF* un *LDF*. Pēc žāvēšanas materiāls tiek formēts, presēts un profilēts. Vienkāršots cieto plātņu izolācijas

ražošanas process ir parādīts 2.2. attēlā. Attīrītas un izžāvētas koksnes šķiedras sajauc ar sveķiem, veido slāni, ko pēc tam presē un cietina. Cietināšana notiek, caur matētu materiālu caurlaižot tvaiku, lai masa tiktu nedaudz uzsildīta. Salīdzinot ar parasto *MDF* ražošanu, darba spiediens ir zemāks un procesā nav nepieciešama karsēta prese. Nelielā temperatūra un nelielais ūdens daudzums sacietina sveķus. Cieto plātņu ražošanā izmanto tikai *pMDI* (polimēru metilēndifenildiizocianātu) sveķus. Cietās plātnes ražo dažādos biezumos no 18 mm līdz 244 mm, to blīvums ir no 100 kg/m^3 līdz 220 kg/m^3. Tās galvenokārt izmanto izolācijai. Neapstrādātās plātnes tiek izlaistas caur profilēšanas iekārtu, lai iegūtu rievotu apdari [28].
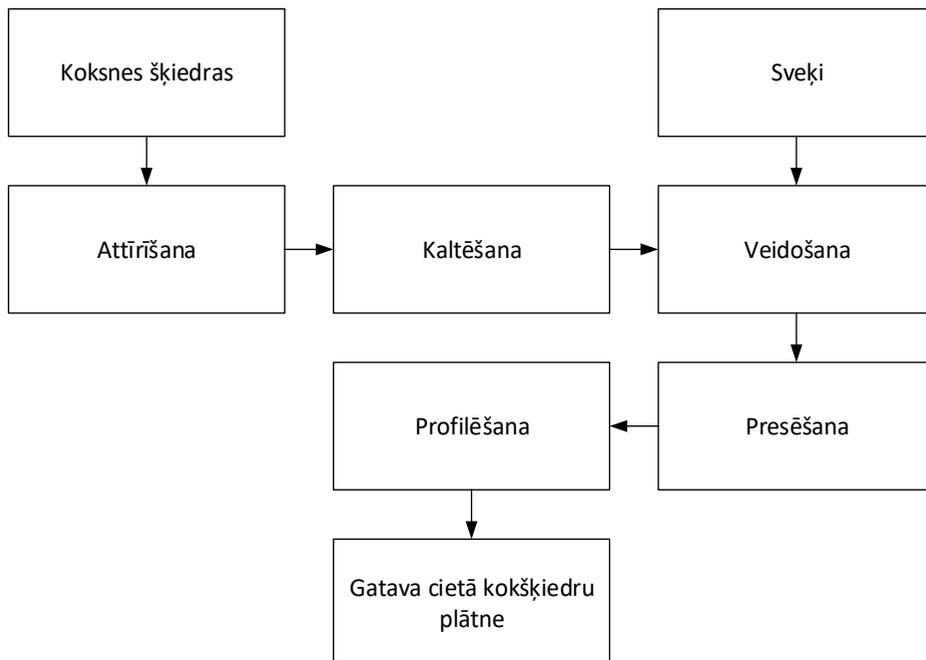
2.2. att. Vienkāršots cieto plātņu ražošanas process [28].

Galvenā cieto plātņu ražošanas izejviela ir mežizstrādes atlikumi, galvenokārt no skujkokiem, kas ir dominējošā Latvijā cērtamo koku grupa. Koksnes šķeldas ražošanā izmanto galvenokārt zarus, mazākus baļķus un, iespējams, celmus, kurus neizmanto parastajā ražošanā. Pieņemts, ka visas skujas un citi zaļumi nokrīt vai tiek noņemti no izejvielām to uzglabāšanas un ražošanas laikā. Lai ražotu kokšķiedras izolācijas plātnes, ir jāiegūst stipras un viendabīgas kvalitātes koksnes šķiedras. Lai gan *MDF* un citu kokšķiedru plātņu ražotāji kā izejvielu tradicionāli izmanto apaļkoksni, jaunas metodes koksnes atkritumu vai ražošanas atlikumu attīrīšanā un šķirošanā ir ļāvušas izmantot alternatīvus koksnes materiālu avotus speciālās ražošanas līnijās [28]. 2013. gadā veiktā pētījumā par šķeldu, kas ražota no mežizstrādes atlikumiem, secināts, ka šādas šķeldas mitruma saturs ir 50 %, un tā ir piemērota izmantošanai maza un vidēja izmēra katlos [91]. Pieņemts, ka no mežizstrādes atlikumu izejvielām iegūtās koksnes šķeldas kvalitāte būs pietiekama, lai ražotu kokšķiedru plātnes.

Jaunā kokšķiedru plātņu izolācijas materiālu bilance ir parādīta 2.3. tabulā. Materiāla blīvums ir pieņemts kā maksimālais iespējamais blīvums cietajam plātnēm no *LPTP* koksnes dokumenta [28]. Materiāla bilance izvēlēta, pamatojoties uz datiem par kokšķiedru plātnēm un izolācijas plātnēm no Meža produktu konversijas faktoru dokumenta [92], pieņemot, ka ir palielināts mizas un samazināts koksnes saturs. Pamatojoties uz izvēlēto materiāla blīvumu un materiālu bilanci, aprēķināts mizas, saistvielu un pildvielu, mitruma un koksnes masas saturs vienā kubikmetrā gatavās izolācijas plāksnes.

Jaunā kokšķiedru plātņu izolācijas materiāla ražošanas procesam izvēlēts standarta sausais ražošanas process no LPTP dokumenta par koksnes plātņu ražošanu [28], kas ir modificēts cieto plātņu ražošanai (2.2. attēls).

<div align="right">2.3. tabula.</div>

<div align="center">Šķiedru plātņu izolācijas materiālu bilance</div>

	Saturs, kg/m^3	Bilance, %	Avots
Blīvums	220	100	[28]
Miza	6,6	3	[93]
Saistvielas un pildvielas	11	5	[93]
Mitrums	13,2	6	[93]
Koks	189,2	86	[93]

Pieņemts, ka, pamatojoties uz vidējo rūpnīcu jaudu nozarē, jaunajā rūpnīcā gadā tiks saražoti 300 000 m^3 šķiedru plātņu izolācijas materiāla [28]. Lai aprēķinātu konkrēto siltumenerģijas un elektroenerģijas daudzumu, kas nepieciešams, lai saražotu vienu kubikmetru materiāla, izmantoti dati par esošajām izolācijas materiālu ražošanas rūpnīcām. Pieņemot, ka esošā ražotne darbojas ar elektrisko jaudu 5 MW un siltuma jaudu 10 MW [94] un 8000 stundas gadā, lai saražotu vienu kubikmetru kokšķiedru plātņu izolācijas materiāla, ražošanas iekārtai būtu nepieciešams 0,13 MWh elektroenerģijas un 0,26 MWh siltumenerģijas. Energoietilpīgāko ražošanas procesu enerģijas patēriņš ir parādīts 2.4. tabulā. Visvairāk enerģijas, galvenokārt siltumenerģijas veidā, patērē koksnes šķiedru žāvēšana, jo šķiedras jāžāvē no 100 % mitruma līdz 5 %. Turklāt žāvētavas ir jāvēdina, izmantojot mehāniskos ventilatorus, kas patērē elektroenerģiju. Otrs energoietilpīgākais process ir šķiedras attīrīšana. Tam nepieciešami jaudīgi motori, kas patērē visvairāk elektroenerģijas. Rafinēšanai ir nepieciešama arī siltumenerģija, lai nodrošinātu karstu tvaiku koksnes šķeldas vārīšanai un mazgāšanai. Šķiedru plātņu paklāja presēšanai ir nepieciešama siltumenerģija tvaika un elektrības veidā preses veltņiem; tomēr cieto plātņu izolācijas ražošanā enerģijas patēriņš ir minimāls, jo nepieciešamā temperatūra ir salīdzinoši zema. Visbeidzot, grupēti visi pārējie procesi, kam nepieciešama elektroenerģija, piemēram, šķeldošana, zāģēšana un profilēšana [28].

Enerģijas patēriņš ražošanai

Ražošanas process	Elektroenerģija, MWh/m³	Siltumenerģija, MWh/m³
Žāvēšana	0,03	0,16
Rafinēšana	0,08	0,08
Spiežot	0,01	0,02
Šķeldošana, zāģēšana, profilēšana	0,01	–
Kopā	0,13	0,26

Lai aprēķinātu materiālā uzkrātā CO_2 iespējamo daudzumu, pārskatīti un izmantoti astoņi dažādi standarti biogēnā oglekļa uzskaitei produktos un dažādi tehniskie standarti aprites cikla analīzei (ACA) ar citām oglekļa uzskaites metodēm un pieejām. Tomēr šajā gadījumā izmantoti tikai tie standarti, kas attiecas uz meža būvmateriāliem un biogēno oglekli. Izmantotos standartus var iedalīt grupās, kas attiecas tikai uz būvmateriāliem (ISO-21930, EN-15804, CEN/TR-16970, EN-16485), un standartos, kas aptver visus produktus (PAS-2050, ISO/TS-14067, PEF). Standartus var atšķirt arī pēc ģeogrāfiskā pārklājuma, jo daži ir starptautiski standarti (ISO-21930, PAS-2050, ISO/TS-14067), bet citi attiecas tikai uz Eiropu (EN-15804, CEN/TR-16970, EN-16485), PEF), un tiem ir ciešāka saikne ar valsts regulējumu [92], [95], [96]. Tā kā pašlaik nav zinātniskās vienprātības par to, kurš standarts un metode ir vispiemērotākie, izmantota vidējā vērtība, kas iegūta no visiem standartiem.

Pieņemts, ka sākotnējais aprēķins materiālā uzkrātajam CO_2 ir vienāds visiem standartiem, un to aprēķina [95] pēc 1. vienādojuma:

$$m_{CO_2} = m_{sauss}\left(koksne\right) \cdot C_f \cdot \frac{m.m_{CO_2}}{m.m_C},$$ (2.10.)

kur

m_{CO2} – sekvestrā CO_2 masa (kgCO_2);
m_{sauss}(koksne) – gatavajā izstrādājumā esošās koksnes sausais svars;
C_f – procentuālais oglekļa daudzums sausnē (koksnei = 0,5);
$m.m_{CO2}$ – CO_2 molekulārā masa;
$m.m_C$ – oglekļa atommasa.

Aizstājot oglekļa un CO_2 masas, 2.10. vienādojumu var pārveidot:

$$m_{CO_2} = m_{sauss}\left(koksne\right) \cdot 0,5 \cdot \frac{44}{12} = C_f \cdot m_{sauss}\left(koksne\right) \cdot 1,833,$$ (2.11.)

kur

m_{CO2} – gatavajā izstrādājumā piesaistītā CO_2 masa;
m_{sauss}(koksne) – gatavajā izstrādājumā esošās koksnes sausais svars.

Jaunā produkta CO_2 daudzumu aprēķina, izmantojot tikai datus par koksnes un mizas saturu. Pieņemts, ka oglekļa saturs mizā ir tāds pats kā koksnē (50 %).

Lai maksimāli palielinātu jaunā šķiedru plātņu izolācijas materiāla CO_2 uzglabāšanas potenciālu, ir jāpārskata un jāanalizē enerģijas ražošanas avoti ražošanas procesā, jo enerģijas ražošana ir vienīgais nozīmīgākais emisiju avots, kas potenciāli var kompensēt izvairīšanos no produkta materiālā uzkrātā CO_2. Siltumenerģijas un elektroenerģijas ražošana no videi visnekaitīgākajiem atjaunojamiem avotiem būtu labākais veids, kā līdz minimumam samazināt ražošanas radītās emisijas. Tomēr tas ne vienmēr var būt tehnoloģiski un ekonomiski dzīvotspējīgākais risinājums, tāpēc enerģijas ieguve produktu ražošanai ir jāizvērtē vides aizsardzības aspektā, vienlaikus ņemot vērā tehnoloģiskos un ekonomiskos aspektus. Izvērtēti trīs enerģijas ražošanas scenāriji, pamatojoties uz izvēlēto ražošanas iekārtas jaudu: 5 MW elektriskā jauda un 10 MW siltuma jauda [92], pašreizējām tendencēm nozarē un iespējamajām nākotnes tehnoloģijām. Trīs izvēlēto scenāriju tehnoloģiskie, ekonomiskie un vides dati ir parādīti 5. tabulā. Enerģijas ražošanas iekārtu jaudas izvēlētas atbilstoši ražošanas iekārtas nepieciešamajai minimālajai siltuma jaudai 10 MW, jo viss procesa siltums ir jāražo uz vietas, lai apmierinātu vajadzību pēc siltuma un tvaika. Enerģijas ražošanas iekārtas elektriskā jauda var būt mazāka par ražošanas iekārtas elektrisko pieprasījumu, jo elektroenerģiju var piegādāt arī no elektrotīkla. Pirmais scenārijs paredz siltuma un elektroenerģijas ražošanu biomasas koģenerācijas stacijā, kurā kā kurināmo izmantotu koksnes šķeldu. Izvēlētā koģenerācijas tehnoloģija ir koksnes šķeldas katls apvienojumā ar tvaika turbīnu. Otrais scenārijs ir dabasgāzes koģenerācijas stacija ar rūpnieciskiem procesiem labi piemērotu gāzes turbīnas tehnoloģiju. Trešais scenārijs ir koksnes biomasas sadedzināšanas iekārta (*CP*), kas ražo tikai siltumenerģiju, kā kurināmo izmantojot koksnes šķeldu, apvienojumā ar fotoelementu (PV) paneļiem elektroenerģijas ražošanai, izmantojot saules enerģiju.

Lai novērtētu ietekmi uz vidi, katram scenārijam ņemtas vērā piecas dažādas emisiju vērtības: NO_x (slāpekļa oksīdi), CO (oglekļa monoksīds), GOS (gaistošie organiskie savienojumi), PM (cietās daļiņas) un CO_2 (oglekļa dioksīds).

Enerģijas ražošanas scenāriju tehnoloģiskie, ekonomiskie un vides parametri

Parametrs	Koksnes biomasas koģenerācija	Dabasgāzes koģenerācija	Koksnes biomasas $CP + PV$ paneļi	Avoti
Elektriskā jauda, MWe	5	7,5	4	[97], [98], [99]
Siltuma jauda, MWth	12	10,7	12	[97], [98]
Elektriskā efektivitāte, %	25	29,2	–	[98], [100]
Siltuma efektivitāte, %	60	41,4	85	[98], [100]
Kopējā efektivitāte, %	85	70,6	85	[98], [100]
Kapitāla izmaksas, EUR/kW[a]	3310	1510	965[b]	[101]
$O\&M$ izmaksas, %CAPEX	2	2,5	2[b]	[101]
Degvielas izmaksas, EUR/MWh	25	81,2	25	[102], [103]
NO_x emisijas, g/MWh[c]	29	27	9,1	[98], [104]
CO emisijas, g/MWh[c]	8	31,5	2,5	[98], [104]
GOS emisijas, g/MWh[c]	0	27	0	[98], [104]
PM emisijas, g/MWh[c]	44	0	13,6	[98], [104]
CO_2 emisijas, kg/MWh[d]	0	202	0	[105]

[a] Pamatojoties uz koģenerācijas elektrostaciju elektrisko jaudu un *CP* siltumjaudu.

[b] Neietver *PV* paneļu izmaksas.

[c] Attiecas uz elektroenerģiju, kas ražota koģenerācijai, un siltumenerģiju, kas paredzēta *CP*.

[d] Attiecas gan uz saražoto elektroenerģiju, gan siltumenerģiju.

Pieņemts, ka autonomas biomasas sadedzināšanas iekārtas kapitālizmaksas ir par 30 % zemākas nekā tādas pašas siltumjaudas koģenerācijas stacijas izmaksas. Tomēr tās ir pārrēķinātas atbilstoši sadedzināšanas iekārtas siltumjaudas jaudai. Līdzīgi pieņemts, ka autonomās biomasas sadedzināšanas iekārtas emisiju līmenis ir tāds pats kā biomasas koģenerācijas stacijai. Tomēr emisiju līmeņi r pārrēķināti kopējai siltumjaudas efektivitātei 85 %, nevis 60 %, un attiecas tikai uz saražoto siltumenerģiju.

Saules paneļu kapitālieguldījumu izmaksas un ekspluatācijas un uzturēšanas izmaksas izvēlētas atbilstoši saules paneļu uzstādīšanas maksimālajai jaudai. Pieņemts, ka saules paneļu iekārtas ar elektrisko jaudu 4 MWe maksimālā jauda ir 5,4 MWp. Šāda lieluma iekārtas kapitālizmaksas ir 510 EUR/kWp, bet *O&M* izmaksas – 6,5 EUR/kWp [99].

Salīdzinot trīs enerģijas ražošanas scenārijus, izmantojot *TOPSIS* metodi, scenāriji jeb alternatīvas novērtēti, lai atrastu ideālo iespējamo risinājumu. Par vislabāko scenāriju uzskatāma alternatīva, kas ir vistuvāk ideālajam risinājumam [106]. Kritēriji izvēlēti, ņemot vērā ekspertu viedokli, kuru darba profils ir tieši saistīts ar būvniecību, ilgtspēju un inovācijām, kā arī literatūras analīzi. Analīzei izvēlētie kritēriji ir parādīti 2.6. tabulā.

Izvēlētie daudzkritēriju analīzes kritēriji

Tehnoloģiskie kritēriji	Ekonomiskie kritēriji	Vides kritēriji
Kurināmā enerģētiskais saturs, GJ/m^3	Kapitālizmaksas, EUR/m^3	NO$_x$ emisijas, g/m^3
	Degvielas izmaksas, EUR/m^3	CO emisijas, g/m^3
	O&M izmaksas, EUR/m^3	GOS emisijas, g/m^3
	Pirktā/pārdotā elektroenerģija, EUR/m^3	PM emisijas, g/m^3
		CO$_2$ emisijas, kg/m^3

Lai veiktu daudzkritēriju analīzi, ir jānosaka kritēriju svarīgums. Tie noteikti, izmantojot analītiskā hierarhijas procesa (AHP) metodi [106]. Vispirms kritēriji sarindoti pēc svarīguma, piešķirot prioritāti ekonomiskajiem un tehnoloģiskajiem kritērijiem, un pēc tam sarindoti vides kritēriji pēc to globālās sasilšanas potenciāla. Pēc tam noteikti katra kritērija svarīgums atkarībā no to ranga, tādējādi tos savstarpēji salīdzinot.

Izmantojot iegūtos kritēriju svarus, iegūti daudzkritēriju analīzes rezultāti. Tie parādīti kā relatīvās tuvības koeficients ideālajam risinājumam. Rezultātiem var būt vērtība no 0 līdz 1, ideālā risinājuma vērtība ir 1. Jo tuvāk alternatīvas koeficients ir maksimālajai vērtībai 1, jo tuvāk tā ir ideālajam risinājumam.

2.2. Aprites cikla novērtējums (ACN)

Tāpat kā daudzkriteriju lēmumu pieņemšanas metode tika apskatīta no tekstilrūpniecības un kokapstrādes sektoru pusēm, arī aprites cikla analīzi var lietot, pētot tekstilrūpniecības un kokapstrādes sektorus

Jāatsaucas uz aprites cikla analīzes tekstilrūpniecības avotu, jo arī pētījumā "*Uncertainty of Life Cycle Assessment Studies for Blended Textiles*" izmantota bibliometriskā analīze. Izpētot ACN pētījumus par *CO/PES* maisījumiem, identificēta zināšanu plaisa. Ir veikti vairāki pētījumi par šī materiāla ietekmi uz vidi [50], [56], [57], [58], taču tie neaptver detalizētu dzīves cikla inventarizāciju ACI. Veronika Vāgnere arī ir identificējusi šo zināšanu plaisu [50]. Lai izstrādātu pilnīgu ACN *CO/PES* maisījumiem, ir nepieciešams literatūras pārskats. Tas uzlabos izpratni par to, kas līdz šim ir pētīts, kādi pieņēmumi ir veikti jaukto tekstilizstrādājumu ACN un kāpēc nav izstrādāts visaptverošs ACI. Šī pētījuma mērķis ir pārskatīt literatūru par kokvilnas un poliestera maisījumu ražošanas vides novērtējuma pētījumiem un identificēt, kādi pieņēmumi līdz šim ir veikti un kā šie pieņēmumi varētu ietekmēt novērtējumu. Ir zināms, ka tekstilizstrādājumu ražošana un patēriņš veicina vides degradāciju un SEG emisijas, taču šīs ietekmes faktiskie apmēri joprojām nav skaidri un tiek apspriesti [44]. Tādējādi solis tuvāk pilnīgai dzīves cikla inventarizācijai var palīdzēt precīzāk novērtēt tekstilizstrādājumu ietekmi uz vidi, uzlabojot zināšanas par to ilgtspējību.

ACN ir vispāratzīts instruments, ko izmanto, lai novērtētu visu aprites cikla darbību ietekmi uz vidi. To izmanto, lai kvantitatīvi noteiktu produkta vai procesa ietekmi uz vidi. Starptautiskā standartizācijas organizācija (*ISO 14040*) nosaka, ka ACN jāievēro sistēma, kas sastāv no

četriem savstarpēji saistītiem posmiem: mērķis un darbības joma, aprites cikla inventarizācija (ACI), aprites cikla ietekmes novērtējums (ACIN) un interpretācija [107].

Analīze sākas ar pētījuma mērķa, funkcionālās vienības (FV), sistēmas robežu, pieņēmumu un ierobežojumu, iedalījuma un izvēlētās ACIN metodes definēšanu sadaļā "Mērķis un darbības joma". Pēc tam tiek izstrādāta ACI, kurā iekļautas ūdens, enerģijas un materiālu ieejas plūsmas un izejas, tostarp atkritumu plūsmas un izplūdes gaisā, ūdenī un zemē. ACIN daļā tiek izvēlētas ietekmes kategorijas, kategoriju rādītāji un raksturošanas modeļi. Līdztekus visiem procesiem interpretācijas procesā tiek novērtēts analīzes pilnīgums, jutīgums un konsekvence, kā arī noteikti secinājumi, ierobežojumi un ieteikumi.

2.2.1. Šķērsām līmētas koksnes aprites cikla novērtējums

Mērķis un darbības joma

Kā piemērs ACN veikšanai ir izvēlēts pētījums par šķērsām līmētas koksnes (*CLT*) atgriezumu pārstrādes ietekmi uz aprites ciklu. Šeit ACN mērķis ir noteikt plātnes, kas izgatavotas no šķērsām līmētas koksnes atgriezumiem, kas iegūti to pārstrādes procesā, ietekmi uz vidi un salīdzināt to ar tradicionāli ražotu šķērsām līmētas koksnes plātnes ietekmi uz vidi. Šajā pētījumā funkcionālā vienība tika definēta kā 1 m³ šķērsām līmētas koksnes plātne.

ACN veikts saskaņā ar ISO 14040/14044 standartu. Analīzei izmantota *SimaPro* programmatūra. Ievaddatu kopas tika ņemtas no datubāzes *Ecoinvent 3.8*. Tika izvēlēta *ReCiPe Midpoint* (H) ACIN metode. Pētījumā netika veikts ražošanas procesu sadalījums. Veikts ACN "no vārtiem līdz vārtiem". Ārpus ražošanas procesa tehniskajām robežām bija resursu ieguve, resursu transportēšana, enerģijas ieguve, iepakojuma materiālu ražošana un iekārtu ražošana.

Pieņēmumi un ierobežojumi

Šajā sadaļā uzsvērti modelēšanas pieņēmumi, izvēloties materiālus vai procesus no *Ecoinvent* datubāzes. Pārstrādes process ir aprakstīts sīkāk, jo no uzņēmuma nebija pieejami dati par jaunu *CLT* ražošanu.

Visur izmantotas nevis sistēmas datu kopas, bet gan vienību datu kopas. Visi izejmateriāli ņemti no tirgus, kā norādīts pie sistēmas robežām, un to ražošana nav ņemta vērā. *CLT* atgriezumi, kas nonāk pārstrādei, ir bez apgrūtinājuma, tāpēc tiek radīta jauna materiālu plūsma. Pārstrādes procesā visi procesi tika veidoti no jauna, izmantojot datubāzē pieejamās materiālu plūsmas.

Materiālu un procesu atrašanās vieta izvēlēta prioritārā secībā: Latvija, Eiropa, pasaule. Transports izmantots tikai *CLT* atgriezumu transportēšanai, un ņemts vērā transports, kravas transports, kravas automašīna, 16–32 metriskās tonnas, EURO5. Visu procesu elekteroenerģijai izmantoti Latvijas elektrotīkla dati: elektroenerģijas tirgus, vidējais spriegums. Vidējais spriegums izvēlēts tāpēc, ka tas izmantots datubāzē pieejamā šķērsām līmētās koksnes ražošanas datu kopā.

Pārstrādātā CLT un jauno CLT ražošanā izmantotas divu veidu līmes: melamīnvielas karbamīda formaldehīds un poliuretāns. Abi šie CLT ņemti no *Ecoinvent*. Pārstrādātā CLT

ražošanā izmanto jaunu ārējo slāni, kas ir skujkoksne, tāpēc tika ņemts šāds datu kopums: zāģmateriāli, dēļi, skujkoksne, kaltēta (u=10 %), ēvelēta.

Pārstrādātā CLT ražošanā rodas divu veidu atkritumi: zāģskaidas un atgriezumi. Atgriezumiem piemīt CLT īpašības, bet tika izvēlēts tuvākais atkritumu veids, ko varēja izmantot modelēšanai. Izvēlētais atkritumu veids bija neapstrādāti datubāzē iekļautie koksnes atkritumi. Tā atkritumu politikas scenārijs bija Latvijas gadījums ar 3 % atklātu dedzināšanu, 15 % atklātu izgāšanu, 4 % nesanitāru izgāšanu, 77 % sanitāru izgāšanu [110]. Otrs atkritumu veids ir zāģskaidas, kas tika uzskatītas par datubāzē iekļautā veida atkritumiem (zāģskaidas, irdenas, mitras, mērītas sausā masā). Analīzē izmanto zāģskaidu atkritumu scenāriju [111]. Tomēr vairumā gadījumu uzņēmumi nodrošina atkritumu nodošanu cietā kurināmā granulu ražotājiem. Šī iemesla dēļ šajā modelētajā scenārijā ir iekļauta zāģskaidu savākšana un uzglabāšana, bet nav ietverts tas, kas ar tām notiek beigās (tās tiek apglabātas poligonā, sadedzinātas u. c.), jo tas var mainīties. Tas tika darīts tāpēc, ka šī procesa ietekme uz vidi kopējā novērtējumā ir nenozīmīga.

CLT pārstrādes uzņēmums neražo neapstrādātu CLT, tāpēc tika veikts literatūras apskats, lai atrastu CLT ražošanas aprites cikla uzskaiti. Izvēlētā produkta vides deklarācija aprakstīja neapstrādāta CLT ražošanu Latvijā, tādējādi nodrošinot datus salīdzinājumam.

Pārskatot vairākas ražojumu vides deklarācijas, atklājās, ka trūkst datu par elektroenerģijas patēriņu un atkritumiem vai arī tie ir apkopoti par vairākiem aprites cikla posmiem, no kuriem daži šajā pētījumā nav iekļauti [112]. Tas, visticamāk, bija datu aizsardzības apsvērumu dēļ. Zinātniskajā literatūrā nebija pieejams pilnīgs CLT ražošanas aprites cikla apraksts, kas būtu salīdzināms ar šajā pētījumā aplūkoto gadījumu, tāpēc izmantots Ecoinvent iestrādātais process, jo tas atspoguļo vidējo situāciju Eiropā [113].

SimaPro iekļautais process (šķērsām līmētu kokmateriālu ražošana) tika modificēts, pielāgojot šī pētījuma robežām un Latvijas gadījumam. Sākotnējo datu pamats ir CLT ražošana Vācijā [19]. Pirmā lielā atšķirība bija sistēmas robežas, jo process ietver iekārtu ražošanu, kas tika izņemta, jo neatbilda šī pētījuma robežām. Tālāk tika izņemts sintētiskais kaučuks, jo Latvijas gadījumā tas netiek izmantots. Tāpat, ņemot vērā nelielo ražošanas jaudu, procesā netika iekļautas smēreļļas, kas nepieciešamas iekārtu uzturēšanai. Tika izņemtas atkritumu plūsmas, kas saistītas ar izslēgtajām izejvielu plūsmām.

Papildu pamatojums iekārtu izņemšanai bija atšķirīgais CLT un pārstrādātā CLT ražošanas mērogs, jo pārstrādātā CLT ražošana ir tikai izmēģinājuma mērogā, atbilstošs iekārtu salīdzinājums būs iespējams pēc pārstrādātā CLT ražošanas palielināšanas vismaz līdz TRL9.

2.2.2. Aprites cikla novērtējums tekstila pārstrāde

ACN datu avoti ir gan datus kopas, kas satur uzņēmuma novērojumus, kā tas tika iepriekš apskatīts pētījumā par šķērsām līmētas koksnes aprites cikla novērtējumu, gan datu kopas, kas iegūtas no literatūras analīzes, p iemēram, apskatot ierobežojumus un pieņēmumus, kas ir izmantoti kokvilnas un poliestera maisījumu vides novērtējumā.

Šajā gadījumā literatūras analīzei izmantota ACN metode. Analīzes mērķis bija novērtēt iespējamo ietekmi uz *CO/PES* (kokvilnas un poliestera) jaukto tekstilizstrādājumu vides novērtējumiem, kas radušies pieejamo datu un literatūrā izdarīto pieņēmumu atšķirību dēļ.

Visdetalizētākais ACN izmantots kā bāzes scenārijs, bet pārējie scenāriji tika izveidoti, mainot datus, kas pārklājas. Rezultāti nesniegs kvantitatīvus datus. Tā vietā secinājumi tiks izmantoti, lai pārbaudītu ACN rezultātu atšķirības, jo scenāriji balstīti uz bāzes scenārija ievaddatiem. Tas nozīmē, ka tika mainīti tikai tie parametri, kuri pārklājas, bet pārējie palika nemainīgi. Ir svarīgi atzīmēt, ka katram pētījumam, uz kura ir balstīti scenāriji, ir dažādi ievaddati un procesi ar dažādām tehnoloģijām. Izmantots ACN "no šūpuļa līdz kapam" un aptver šādus procesus: šķiedru ekstrakcija, dzijas ražošana, aušanas sagatavošana (izmēru noteikšana), aušana, pirmapstrāde, nepārtraukta krāsošana un auduma apdare. Detalizētāks procesu apraksts sniegts Veronikas Vāgneras et. al. pētījumā [50]. ACN veikts saskaņā ar ISO 14040/14044 standartu. Analīzei izmantota programmatūra *SimaPro*. Šajā pētījumā funkcionālā vienība tika definēta kā 1 kg kokvilnas un poliestera sajaukta tekstilizstrādājuma. Ievaddatu kopas tika ņemtas no *Ecoinvent 3.8* datubāzes. *ReCiPe Midpoint* (H) V1.08 dzīves cikla ietekmes novērtējuma metode tika izvēlēta, jo tā izmantota arī ACN pētījumā par līdzīgiem tekstilizstrādājumiem [50].

2.3. Bibliometriskā analīze

2.3.1. Jaukta tekstila aprites potenciāla bibliometriskā analīze

2.2.2. nodaļā apskatīts datu ACN analīzes aspekts, novērtējot ierobežojumus un pieņēmumus, kas izmantoti kokvilnas un poliestera maisījumu vides novērtējumos. Šie dati iegūti ar bibliometriskā analīzes palīdzību.

Literatūras analīze sākas ar bibliometrisko analīzi, lai gūtu priekšstatu par pētāmo jomu un noteiktu galvenos atslēgvārdus turpmākai izmantošanai. Bibliometriskā analīze ir kvantitatīvā metode, ko izmanto, lai novērtētu pašreizējo stāvokli pētniecības jomā, aplūkojot savstarpējās attiecības starp zinātniskajām publikācijām šajā jomā [114]. Analīzes pamatā ir liels skaits zinātnisku publikāciju, kuras tiek analizētas, izmantojot programmatūru, kas izmanto statistikas un tīkla rīkus. Šajā pētījumā izmantota programmatūra *VOSviewer*. Mērķis bija gūt ieskatu pētījumos par jauktu tekstilizstrādājumu, īpaši *CO/PES* maisījumu, ietekmi uz vidi. Bibliometriskajai analīzei ieteicamas *Scopus* vai *Web of Science* datubāzes [115]. Šajā pētījumā izmantota *Web of Science* datubāze, jo atbilstoši noteiktajiem atslēgvārdiem tika atrasts 381 rezultāts, savukārt *Scopus* datubāzē tika atrasti 211 rezultāti. Atslēgvārdi tika kombinēti starp ietekmi uz vidi un vides novērtējumu un starp jauktiem tekstilizstrādājumiem, tekstilizstrādājumu maisījumiem un kokvilnas poliestera maisījumiem. Kopumā atlasīti seši atslēgvārdi, kas atdalīti ar "*OR*". Pēc pirmās analīzes oriģinālajā datnē tika identificēti un mainīti vairāki vārdi, jo tiem bija tāda pati nozīme, bet atšķirīga pareizrakstība. Pēc tam tika izvēlēts gadījumu slieksnis. Atslēgvārdu gadījumu skaits virs 12 tika izvēlēts, jo tika veidotas loģiskās kopas, un vārdu skaits nebija pārāk liels. Izmantojot identificētos atslēgvārdus, veikta turpmāka literatūras analīze, lai apkopotu pētījumus par *CO/PES* maisījumu ražošanas vides novērtējumu. Lai to izdarītu, galvenokārt izmantoti atslēgvārdi no aprites cikla novērtēšanas kopām, bet reizēm izmantoti atslēgvārdi no citām kopām, piemēram, notekūdeņu un toksicitātes. Papildus jau esošajiem atslēgvārdiem tika meklēti arī pētījumi par konkrētiem tekstilizstrādājumu ražošanas posmiem (dzijas izmēru, aušanu, priekšapstrādi, krāsošanu un apdari). Izmantotas trīs datubāzes: *Web of Science*, *Google Scholar* un *Scopus*. Pētījumi tika

kvalitatīvi novērtēti, un turpmākai analīzei atlasīti tikai tie, kuriem bija pietiekami kvantitatīvi dati. Pēc literatūras apskata izpētīta arī *Ecoinvent* datubāze, jo tā izmantota turpmākajā analīzē. Datubāze satur datu kopas par dažādām nozarēm, piemēram, enerģijas ražošanu, transportu un materiāliem. Tajā ir vairāk nekā 20 000 savstarpēji saistītu datu kopu [116]. Tāpēc tika pārbaudīts, vai datubāzē ir iekļauti *CO/PES* maisījumu ražošanas procesi.

2.3.2. Energoaudita prakšu bibliometriskā analīze

Bibliometriskās analīzes metode lietota arī pētījumā par energoauditiem. Pētījumam par energoaudita praksi atbilstošās literatūras identificēšana ietvēra rezultātu analīzi par dokumentiem un žurnālu rakstiem, kas publicēti laikā no 2009. līdz 2024. gadam. Bibliometriskā analīze veikta pētījumiem, kas publicēti uzticamos zinātniskos publikāciju kopsavilkumos, kuri atrodami citēšanas datubāzēs *Scopus* un *MDPI*. Šīs datubāzes ietver plašu tēmu klāstu, sniedz publikāciju metriku un ir brīvi pieejamas, kas atvieglo to izmantošanu. Meklēšana koncentrējās uz energoaudita praksi, energoefektivitātes pasākumiem un saistītajiem tiesību aktiem ES dalībvalstīs.

Meklēšana veikta, izmantojot vairākus vaicājumus. Atlasītie vaicājumu iestatījumi ietvēra definētu atslēgvārdu meklēšanu dokumentu nosaukumos, kopsavilkumos un atslēgvārdos; daži vaicājumi ietvēra arī meklēšanu visos laukos vai pilnā tekstā. Vaicājumos izmantotie atslēgvārdi tika iekļauti pēdiņās. Pirmie seši vaicājumi (sk. 3.10. tabulu 3.3.2. sadaļā) paredzēti, lai veiktu visu publicēto dokumentu meklēšanu par energoauditu tēmu laika posmā no 2009. līdz 2024. gadam *Scopus* datubāzē. 7.–9. vaicājums izmantoti, lai laika posmā no 2009. līdz 2024. gadam meklētu visus publicētos žurnālu rakstus *MDPI* datubāzē. 10. vaicājums izmantots, lai meklētu tiesību aktus *EUROPA SEARCH*, kas pieejams Eiropas Komisijas oficiālās tīmekļa vietnes meklēšanas sadaļā. 10. vaicājumam nebija laika ierobežojuma.

2.4. Sistēmdinamika

Pamatojoties uz literatūras pārskatu, tika definēti trīs pētījuma jautājumi: (a) Kāds apģērbu daudzums tuvākajā nākotnē nonāks poligonos? (b) Vai ES šķirošanas kapacitātes palielināšana būs pietiekama, lai sasniegtu aprites ekonomikas mērķus? (c) Kas veicina aprites ekonomiku – tekstilizstrādājumu šķirošana vai patēriņa samazināšana? Šī pētījuma mērķis ir analizēt aprites ekonomikas potenciālu modes tekstilizstrādājumu vērtību ķēdē ES līmenī, izmantojot sistēmdinamikas modelēšanu. Tekstilizstrādājumu daudzums, kas nonāk poligonos bāzes scenārijā, tiks izmantots, lai novērtētu aprites ekonomikas potenciālu, jo tas atspoguļo zaudēto vērtību, ko varētu atgūt, ieviešot aprites prakses visā vērtību ķēdē. Rezultāti parādīs ES progresu ceļā uz aprites ekonomiku un ilgtspējību, kā arī to, vai ES politikas mērķi tekstilizstrādājumiem var tikt sasniegti līdz 2030. gadam. Tas arī atbildēs uz jautājumu, kas virza aprites ekonomiku tekstila sistēmā.

Sistēmdinamika ir pētniecības metode, kas pēta sarežģītu sistēmu uzvedību un to radītos izaicinājumus. Mērķis ir analizēt sistēmu struktūru, lai iegūtu dziļāku izpratni par to uzvedību un tās cēloņiem [117]. Šo metodi parasti izmanto akadēmiskajā vidē, lielie uzņēmumi, konsultāciju uzņēmumi un valdības, lai uzlabotu stratēģijas formulēšanu, politikas izstrādi un

lēmumu pieņemšanu sarežģītās un dinamiskās jomās [118]. Tai ir matemātiskās modelēšanas pieeja. Sistēmdinamikas modelēšana ir plaši izmantota, lai pētītu vērtību/piegādes ķēdes un aprites ekonomikas ceļus, piemēram, reverso loģistiku [118], [119], slēgtā cikla piegādes ķēdi [120], otrreizējās pārstrādes sistēmu [121], materiālu plūsmas [122], [123], aprites ekonomika vairākos mērogos [124]. Sistēmdinamikas modelēšanas pieeja šim pētījumam tika izvēlēta, lai izpētītu modes tekstilizstrādājumu vērtību ķēdi, jo tā ir piemērota sistēmas struktūras, uzvedības, elementu mijiedarbības apskatei un iespējams izveidot slēgta cikla sistēmas. Modeli var simulēt laika gaitā, lai sniegtu priekšstatu par nākotnes situāciju. Turklāt, izmantojot politikas instrumentus, var izstrādāt un pārbaudīt vērtību ķēdes problēmu risinājumus. 2.3. attēlā parādīti visa pētījuma soļi un to secība. Politikas instrumentu izstrāde tiek parādīta secīgi, taču tas nenozīmē, ka viens ir svarīgāks par otru vai ka secība ir nemainīga.
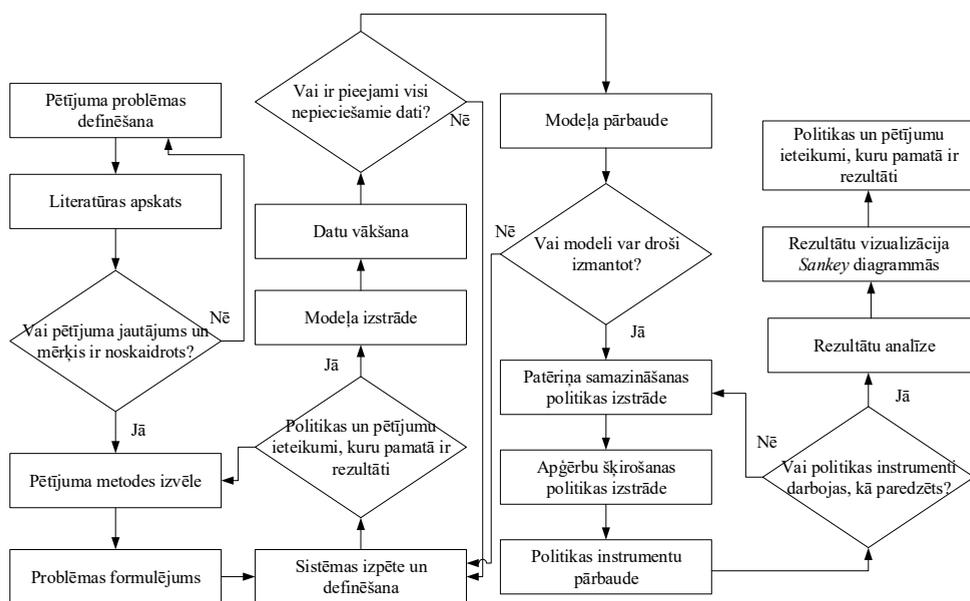
2.3. attēls. Pētījuma metodoloģijas algoritms.

Sistēmdinamikas modelēšana

Pētījuma piemērā [What Drives the Circular Economy? Textile Sorting or Consumtion Reduction] tika izvēlēta sistēmdinamikas modelēšana. Tam izmantots *Stella Architect*. Šī programmatūra ļauj izveidot sistēmas struktūru un modelēt sistēmu laika gaitā. Modeļa galvenie elementi ir krājumi, plūsmas un parametri, kas ir savstarpēji saistīti. Saites un mijiedarbība starp komponentiem veido atgriezeniskās saites. Ir divas atgriezeniskās saites: pozitīvas virzības un negatīvas balansēšanas saites [117]. Pozitīva virzības saite ir tad, kad savienotie elementi mainās vienā virzienā vai kad pāra skaits elementu mainās pretējā virzienā. Negatīvā balansēšanas saite ir tad, kad nepāra skaits savienoto komponentu mainās pretējos virzienos.

Sistēmdinamikas modeļa izstrāde ietver piecus galvenos soļus [117]. Tie ir problēmu formulēšana, dinamikas hipotēžu izvirzīšana, modeļa formulēšana un simulācija, modeļu pārbaude un politikas izstrāde un novērtēšana. Veidojot šādu modeli, ir ierasts pārskatīt iepriekšējās darbības, lai sasniegtu vēlamos rezultātus.

Problēmas formulējums

Pirmais solis ir definēt problēmu un definēt bāzes scenāriju, kas grafiski attēlo problēmu laika gaitā. Grafikā bieži ir attēlota galveno mainīgo uzvedība [125]. Galvenā dinamiskā problēma šajā pētījumā ir tāda, ka apģērbu patēriņš pieaug strauji, kamēr dzīves ilgums samazinās. Tas ietekmē apglabājamo apģērbu apjomu un šķiroto apģērbu īpatsvaru. Prognozējošā modeļa mērķis ir prognozēt, cik liela daļa no ES patērētā apģērba 2030. gadā tiks apglabāta izgāztuvē un cik daudz tiks sašķirots.

Sistēmas izpēte un definēšana

Ražošanas un eksporta rādītāji liecina, ka Ķīna ir pasaulē lielākā visu tekstilizstrādājumu ražotāja un eksportētāja, bet ES ir otra lielākā dalībniece [87]. Tekstilizstrādājumiem ir būtiska nozīme ES virzībā uz aprites ekonomiku, ilgtspējību un klimatneitralitāti, jo tā ir ceturtā lielākā patēriņa kategorija pēc pārtikas, mājokļa un transporta, ņemot vērā primāro resursu un ūdens patēriņu, un piektā lielākā SEG emisiju ziņā. [126]. Tekstilizstrādājumi veido 4–6 % no ES ekoloģiskās pēdas [69]. Ir svarīgi uzsvērt, ka 85–93 % no ietekmes uz vidi notiek ārpus ES, un 76 % no SEG emisijām, ko rada ES tekstilizstrādājumu patēriņš, rodas arī ārvalstīs [87]. Tas ir tāpēc, ka, lai apmierinātu pieprasījumu, 97 % no ES patērētā apģērba un mājas tekstilizstrādājumiem tiek importēti no citām valstīm [66].

Lai izveidotu sistēmas struktūru, ir jāsaprot modes tekstilizstrādājumu vērtību ķēde. Vērtību ķēde galvenokārt ir lineāra, sākot no izejmateriālu ieguves un pārstrādes līdz aprites beigu stadijai [127]. Ir septiņi galvenie posmi, kas ir savstarpēji savienoti ar transportu, izņemot gadījumus, kad vienā vietā notiek vairāki ražošanas posmi. Darbības piemēri ir šķiedru ekstrakcija, dzijas ražošana, audumu ražošana, apģērbu ražošana, izstrādājumu mazumtirdzniecība, lietošanas fāze un kalpošanas laika beigas.

Šķiedru ekstrakcijas posms ietver šķiedru ekstrakciju un apstrādi. Tās ietekme uz vidi galvenokārt ir atkarīga no izejmateriāla veida: mākslīgās šķiedras vai dabiskās šķiedras. Labi zināmās dabiskās šķiedras ir kokvilna, vilna, zīds, lins un kaņepes. Mākslīgās šķiedras var iedalīt pēc to polimēru izcelsmes. Šķiedras var iegūt no dabīgiem polimēriem, piemēram, celulozes šķiedrām (viskoze, liocels un modāls) vai sintētiskiem polimēriem (neilona, poliestera un akrila) [46]. Poliesteris ir visplašāk izmantotā izejviela, kas veido apmēram pusi no visām šķiedrām. Jāņem vērā, ka dabīgajām šķiedrām ne vienmēr būs mazāka ietekme uz vidi. Piemēram, lai saražotu 1 kg kokvilnas [2], ir nepieciešami līdz 4300 litriem ūdens, un kokvilnai kā kultūraugam ir nepieciešams vislielākais pesticīdu daudzums pasaulē [46]. Šis posms veido aptuveni 38 % no kopējām dzīves cikla SEG emisijām [45].

Nākamais dzīves cikla posms ir dzijas ražošana no šķiedrām. Diegu iegūst, vērpjot šķiedras. Vērpšanas posms ietver vairākus mehāniskus procesus, piemēram, šķiedru ķemmēšanu, izlīdzināšanu un vērpšanu [46]. Šķiedras pārveidošanas stadijā rodas atkritumi, kas rada

izejvielu zudumus aptuveni 3 % apmērā [2]. Dzijas ražošana veido aptuveni 8 % no kopējām dzīves cikla SEG emisijām [45].

Audumu ražošanā ietilpst adīšana, aušana, mitrā apstrāde [128]. Mitrā apstrāde ietver dziju un audumu apstrādi, izmantojot ķīmiskas vielas un krāsvielas. Šis process rada vislielāko notekūdeņu daudzumu. Vidēji 1 kg auduma ražošanai nepieciešami aptuveni 200 litri ūdens [46]. Visā pasaulē šī procesa notekūdeņi veido aptuveni 20 % no visiem notekūdeņiem [45]. Auduma ražošana veido 6 % un mitrā apstrāde 15 % no dzīves cikla SEG emisijām, kas kopā veido 21 % [45].

Tekstilizstrādājumu ražošana beidzas ar galaprodukta izgatavošanu. Šajā posmā audumi tiek piegriezti un šūti, lai iegūtu vēlamo galaproduktu [45]. Ir pievienoti arī citi estētiski vai funkcionāli papildinājumi, piemēram, pogas un rāvējslēdzēji. Galaprodukta ražošanas ietekme uz vidi ir salīdzinoši zema, jo tas veido tikai 4 % no kopējām dzīves cikla SEG emisijām [45]. Tomēr šis process rada visvairāk tekstilizstrādājumu atkritumu no visiem ražošanas posmiem. Piemēram, pētījums par apģērbu ražošanu atklāja, ka mazākās rūpnīcās rodas vairāk tekstilizstrādājumu atkritumu nekā lielākās (attiecīgi 39 % un 25 %) [16]. Šos atgriezumus galvenokārt apglabā vai izmanto enerģijas iegūšanai, taču pētījumā secināts, ka aptuveni 50 % līdz 80 % var pārstrādāt jaunos apģērbos.

Mazumtirdzniecība arī ir daļa no dzīves cikla, jo tā rada daļu no SEG emisijām un pārdošanas atlikumiem. Pasaulē ik gadu tiek ražoti un veikalos ievietoti aptuveni 150 miljardi apģērbu [45]. 30 % no šiem apģērba gabaliem netiek pārdoti, un aptuveni tikpat daudz tiek pārdoti ar atlaidi. Mazumtirdzniecība veido 3 % no kopējām dzīves cikla SEG emisijām [45].

Lietošanas fāze ir otrs lielākais SEG emisiju avots pēc ražošanas. Tā veido aptuveni 20 % no kopējām aprites cikla SEG emisijām [45]. Tas galvenokārt ir saistīts ar izstrādājumu mazgāšanu, žāvēšanu un gludināšanu, kas rada ievērojamu enerģijas un ūdens patēriņu [65]. Turklāt tiek radīts mikroplastmasas piesārņojums. Pasaulē katru gadu veļas mazgāšanas rezultātā rodas aptuveni pusmiljons tonnu plastmasas mikrošķiedru. Tas rada okeāna piesārņojumu, kas ir 16 reizes lielāks nekā kosmētikas nozarē [2]. Šīs šķiedras nāk no mākslīgajiem materiāliem, sākot no 64 mg uz 1 kg polipropilēna līdz 319 mg uz 1 kg viskozes [129]. Šis posms galvenokārt ir patērētāju ziņā. Patēriņš ar katru gadu pieaug, kamēr lietošanas ilgums samazinās. Tiek prognozēts, ka līdz 2030. gadam apģērbu patēriņš varētu pieaugt par 63 % [53]. Nav konkrētas prognozes par apģērba patēriņa ilgumu, taču pēdējo 15 gadu laikā tas ir samazinājies uz pusi [69]. Pasaulē tekstilizstrādājumu patēriņš ir no 9 kg līdz 27 kg uz cilvēku [86].

Aprites beigu posmu var iedalīt trīs veidos: atkārtota izmantošana, pārstrāde un sadedzināšana vai iznīcināšana. Pirmkārt, tekstilizstrādājumi tiek savākti atsevišķi šķirošanai vai kopā ar sadzīves atkritumiem. Pēc patēriņa kopā ar sadzīves atkritumiem savāktie materiāli tiek apglabāti izgāztuvēs vai izmantoti enerģijas reģenerācijai. Šķiroto tekstilizstrādājumu īpatsvars dažādās valstīs ir atšķirīgs. ES tiek šķiroti 38 % tekstilizstrādājumu, bet, aplūkojot dalībvalstis atsevišķi, šī daļa svārstās no 4,5 % Latvijā līdz 45 % Nīderlandē [14] un pat 75 % Vācijā [2]. Tekstilizstrādājumu apglabāšana izgāztuvēs un sadedzināšana rada aptuveni 3 % no kopējām dzīves cikla SEG emisijām [45].

Sašķirotās drēbes tiek pārstrādātas vai izmantotas atkārtoti. Tekstilizstrādājumu atkārtota izmantošana ir videi draudzīgāka nekā pārstrāde [130]. Pārstrāde var būt vai nu slēgtā cikla otrreizējā pārstrāde jeb audumu pārstrāde produktā, kas paliek tekstilizstrādājumu vērtību ķēdē, vai tekstilizstrādājumu pārstrāde (visbiežāk mehāniska) produktā, kas neietilpst tekstilizstrādājumu vērtību ķēdē, un tai ir zemāka pievienotā vērtība [131]. Slēgtā cikla otrreizējā pārstrāde netiek plaši izmantota, jo, kad pārstrādātie materiāli nonāk tekstilizstrādājumu vērtību ķēdē, tie visbiežāk tiek atgūti no plastmasas pudelēm [132]. Šī prakse neveicina atkritumu samazināšanu tekstilizstrādājumu sistēmā un neatbalsta slēgtā cikla otrreizējo pārstrādi. Aptuveni 50 % līdz 75% no šķirotajiem tekstilizstrādājumiem tiek izmantoti atkārtoti [66]. Tomēr arī šī daļa ir ļoti atkarīga no valsts, jo to ietekmē iedzīvotāju lietošanas paradumi un izmantotā šķirošanas metode.

Dinamiskās hipotēzes izstrāde

Dinamiskā hipotēze ietver galveno krājumu, plūsmu un parametru definēšanu, kas saistīti ar bāzes uzvedību. Modeļa vadošie krājumi ir izgāztuvē nonākušie apģērbi, pieejamie apģērbi un īpatnējais apģērbu patēriņš. Plūsmas, kas ietekmē šos krājumus, ir apģērbu apglabāšana izgāztuvēs, apģērbu patēriņš un apģērbu izmešana, patēriņa izmaiņas. Turklāt jau sākotnēji bija jānosaka galvenie faktori, kas ietekmē šīs plūsmas un rada atgriezenisko saiti. Kopumā plūsmas izmaiņas modelī ietekmē četri galvenie parametri. Tie ir **apģērba kalpošanas laiks**, **apģērbs izgāztuvei**, **īpatnējā patēriņa pieauguma temps** un **izaugsmes temps**.

Modeļa formulēšana un simulācija

Nākamajā procesa solī modelis tika aprakstīts ar vienādojumiem, kas attēlo sakarības starp modeļa elementiem, un dinamiskā hipotēze tika pārveidota par datormodeli un atjaunināta ar citiem sistēmas elementiem. Sākotnēji tika izveidota sistēmas galvenā struktūra, un daļas tika savienotas ar atgriezenisko saiti pirms vienādojumu un ievades datu formulēšanas un ievietošanas. Apģērbu apjomi tika noteikti tonnās, un laika vienība bija gads Sistēmas struktūru var iedalīt divās daļās: apģērbu ražošana un patēriņš un apģērbs pēc patēriņa. Arī pēcpatēriņa apģērbs ir iedalīts divās daļās: viena nonāk šķirošanā, bet otra – sadzīves atkritumos. Pilns modelis skatāms 6. attēlā.
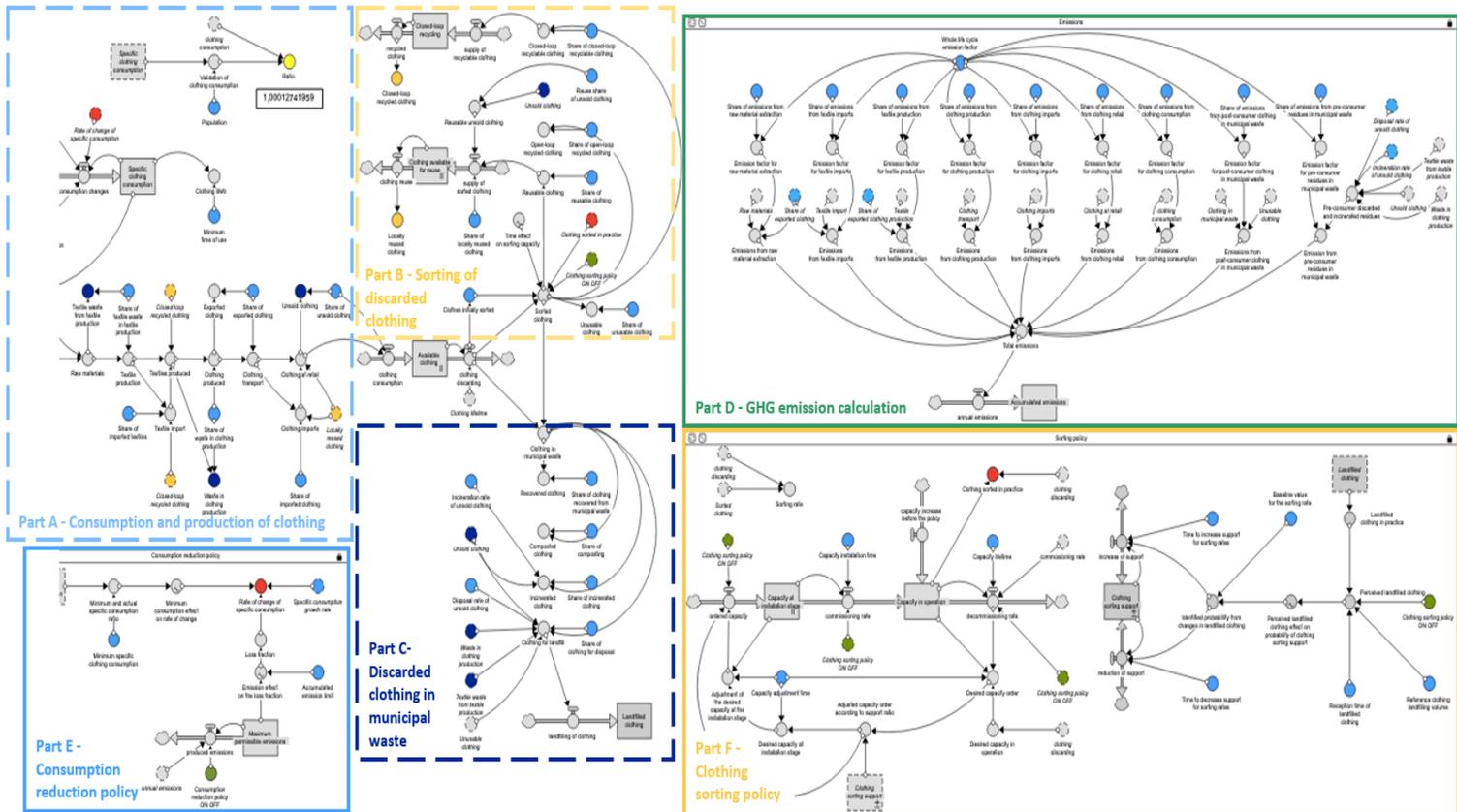
2.4. attēls. Apģērba vērtību ķēdes sistēmdinamikas modeļa struktūra.

Apģērbu ražošanas un patēriņa struktūra parādīta 2.5. attēlā. Šī sistēmas daļa ir atkarīga no **apģērba īpatnējā patēriņa**. Tas ietekmē **izaugsmes tempu**, nosakot pieprasījuma apmierināšanai nepieciešamo ieguldījumu. Šo modeli nevar izmantot, lai prognozētu apģērbu patēriņu, jo tas palielinās atbilstoši **īpatnējā patēriņa pieauguma tempam**, kas ir nemainīgs parametrs modelī. Šajā un citās modeļa daļās nemainīgie parametri ir atzīmēti gaiši zilā krāsā, atkritumi, kas radušies ražošanas un pārdošanas laikā, ir atzīmēti tumši zilā krāsā, un apģērbs, kas atgriežas ciklā, ir atzīmēts ar dzeltenu krāsu.

Apģērbu ražošana ir iedalīta trīs daļās: tekstilizstrādājumu ražošana, apģērbu ražošana un apģērbu tirdzniecība. Tekstilizstrādājumu ražošanai ir vajadzīgas tādas izejvielas kā šķiedras un dzijas. Tekstilizstrādājumi tiek piegādāti apģērbu ražošanai, kur tiek pievienoti importēti tekstilizstrādājumi un slēgtā ciklā otrreizēji pārstrādāti apģērbi. Sistēma ņem vērā arī eksportēto apģērbu, lai turpmākajos modeļa izstrādes posmos varētu pievienot politikas instrumentus, kas ietekmē eksporta īpatsvaru. Pārdošanā ietilpst apģērbi, kas ražoti pēc eksporta un importēti. Atlikumi rodas visos ražošanas posmos. Atkritumu rašanās apģērbu ražošanā ārpus ES vēl ir jāiekļauj modelī.
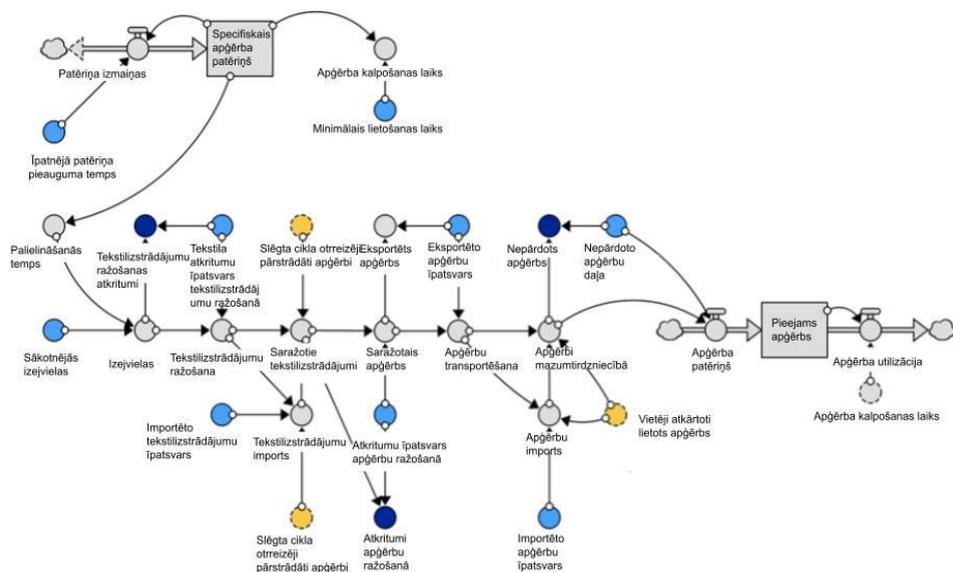
2.5. attēls. Sistēmas A daļa: apģērbu patēriņš un ražošana.

Pēc tam, kad patērētājs atbrīvojas no drēbēm, tās tiek šķirotas vai izmestas sadzīves atkritumos. Šķirošanas sistēmas struktūra ir parādīta 2.6. attēlā. Šo daļu ietekmē **laika ietekme uz šķirošanas jaudu**, kas ir prognozētais ikgadējais jaudas pieaugums. Sašķirotie apģērba gabali tālāk tiek sadalīti četrās plūsmās. Apģērbu izmanto atkārtoti un pārstrādā, taču ir arī piesārņotas drēbes, kuras nevar izmantot atkārtoti vai pārstrādāt, un tāpēc tās nonāk izgāztuvēs. Ir divi pārstrādes veidi: slēgtā cikla un atvērtā cikla otrreizējā pārstrāde. Ir izveidoti papildu krājumi ar plūsmām, lai izveidotu 1/*DT* aizkavi atkārtoti izmantotam un slēgta cikla otrreizēji pārstrādātam apģērbam. Modeļa laika solis (*DT*, *Delta Time*) ir 0,25 gadi. Aizkave rodas, jo šo

parametru vērtības tiek ievadītas apģērba ražošanā un mazumtirdzniecībā, veidojot apriti. Tiek pieņemts, ka visi slēgtā cikla pārstrādātie apģērbi atgriežas vietējā vērtību ķēdē.
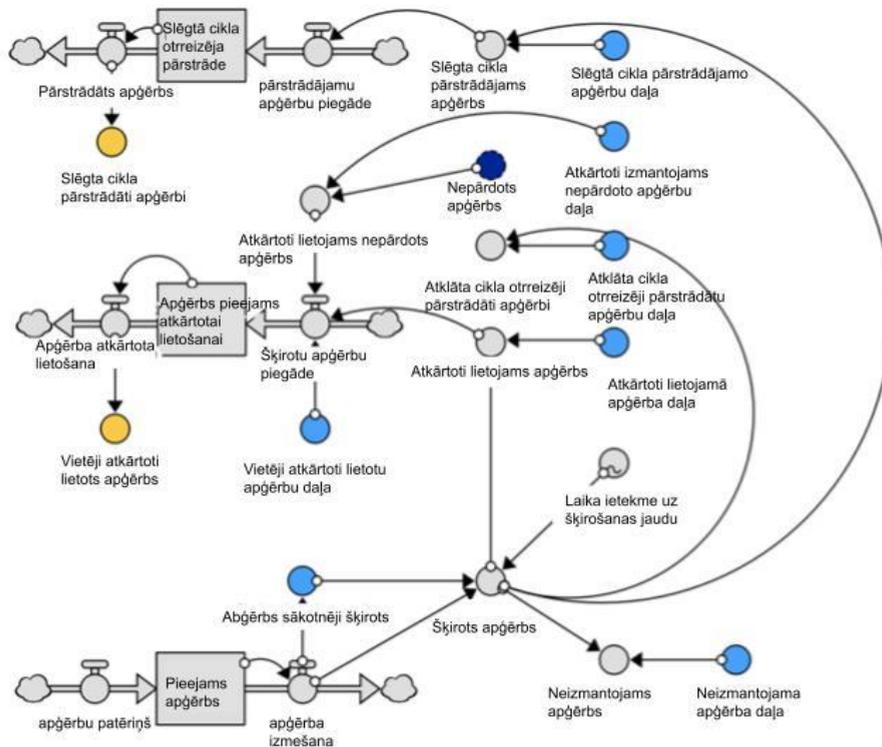
2.6. attēls. Sistēmas B daļa: izmesto apģērbu šķirošana.

Ja pieņem, ka izmestās drēbes neietilpst šķirošanas plūsmā. Tādā gadījumā tās nonāk sadzīves atkritumu plūsmā (2.7. attēls). Apģērbu var reģenerēt no sadzīves atkritumiem, kompostēt, sadedzināt vai apglabāt izgāztuvē. Šai sistēmas daļai tiek pievienoti ražošanas un pārdošanas atkritumi. Tiek pieņemts, ka ražošanas atliekas nevis sadedzina, bet apglabā izgāztuvēs. Pārdošanas atlikumi tiek sadedzināti un apglabāti izgāztuvēs. Sadedzināšana ietver arī enerģijas atgūšanu, bet ne obligāti.
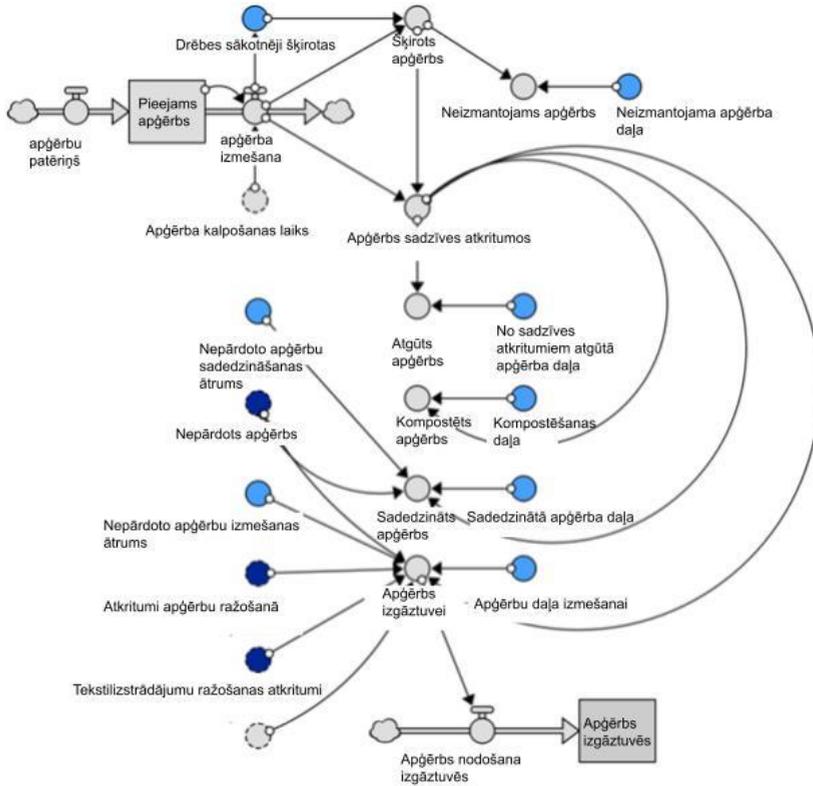
2.7. attēls. Sistēmas C daļa: sadzīves atkritumos izmests apģērbs.

Papildus primārajai sistēmai tika izveidota SEG emisiju sistēma. Tā kā apģērbs tiek uzskatīts par vienu plūsmu un nav sadalīts pēc lietojuma un izmantotajiem materiāliem, kopējās SEG emisijas aprēķinātas, izmantojot visa dzīves cikla SEG emisijas koeficientu. Sistēmas uzbūve ir parādīta 2.8. attēlā.
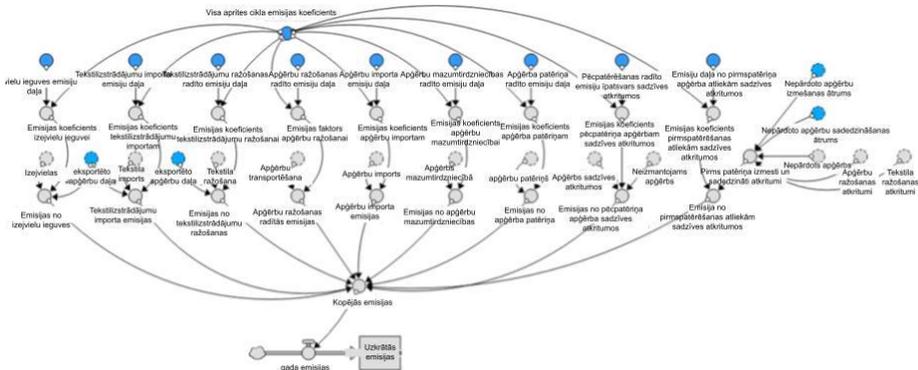
2.8. attēls. Sistēmas D daļa: SEG emisiju aprēķins.

Kad modeļa struktūra bija pabeigta, matemātiskajiem vienādojumiem bija jāapraksta attiecības starp elementiem. Elementiem, kas modelī attēloti pelēkā un tumši zilā krāsā, vērtības ir norādītas ar vienādojumiem. Modelis ietver aptuveni 90 vienādojumus, četrus vienādojumus, kas izteikti grafiski, un veikti vairāki papildu aprēķini, lai iegūtu modelī izmantotās konstantes.

Kā minēts iepriekš, sistēmas sākuma daļa ir atkarīga no konkrētā apģērba patēriņa. **Sākotnējais apģērba patēriņš uz vienu iedzīvotāju** tika iegūts, dalot kopējo apģērbu patēriņu ES 2018. gadā, kas bija 4,38 miljoni tonnu [66], ar iedzīvotāju skaitu 446 miljoni cilvēku [133]. Līdz ar to apģērba patēriņš uz vienu iedzīvotāju tika aprēķināts 9,82 kilogramu apmērā. Parametram "**īpatnējā patēriņa pieauguma temps**" tika izmantots saliktā gada pieauguma ātruma vienādojums, ņemot vērā, ka tiek prognozēts, ka apģērbu patēriņš līdz 2030. gadam pieaugs par 63 % [67]. Bāzes gads netika minēts, tāpēc tika pieņemts 2018. gads. Tas pats vienādojums tika izmantots, lai iegūtu ikgadējo apģērba lietošanas laika samazinājumu. Tā kā pēdējo 15 gadu laikā apģērba valkāšanai pavadītais laiks ir samazinājies uz pusi [69], tika pieņemts, ka šī tendence turpināsies līdz 2030. gadam. Sākotnējais apģērba kalpošanas laiks bija 3,3 gadi [68]. Attiecība starp dzīves ilgumu un apģērba īpatnējo patēriņu tika izteikta ar regresijas vienādojumu.

$$P_{lt} = 0,0047 \cdot S_{sc}^{-1,419},$$ (2.12.)

kur

P_{lt} – apģērba kalpošanas laiks (gadi/gadā);

S_{SC} – īpatnējais apģērba patēriņš (t/iedzīvotājs)/gadā.

Pieauguma tempu iegūst, dalot konkrētā gada apģērbu patēriņu ar konkrētā apģērba patēriņa sākuma vērtību. Visi apģērbu ražošanas parametri ir atkarīgi no **izaugsmes tempa** un **sākotnējām izejvielām**. Izejvielu sākotnējā vērtība tika iegūta optimizācijas procesā. Vērtība tika optimizēta, līdz īpatnējais apģērba patēriņš, reizināts ar iedzīvotāju skaitu attiecībā pret apģērbu patēriņa plūsmu, sasniedza vērtību 1000. Iedzīvotāju skaits tika pieņemts nemainīgs, jo *COVID-19* ietekme uz sistēmu netika ņemta vērā, un prognozētās iedzīvotāju skaita izmaiņas līdz 2030. gadam ES nav būtiskas [134].

Secīgi visiem parametriem līdz krājumam "**Apģērbi pieejami**" ir vienādojumi, kuru pamatā ir koeficienti. Piemēram, **tekstilizstrādājumu ražošanas atkritumiem** ir vienādojums, kur izejvielas reizinātas ar ražošanas atlikumu ītatsvaru ražošanā, kas pieņemta kā 0,03 [2]. Tikmēr **tekstila ražošanā** ir vienādojums, kur izejvielas reizinātas ar īpatsvaru no 1-0,03. Tika pieņemts, ka tādas vērtības kā **slēgtā cikla otrreizēji pārstrādāti apģērbi**, kas veido apriti sistēmā, samazina importu, nevis ražošanu. Piemēram, tekstilizstrādājumu importu aprēķina pēc 2.13. vienādojuma:

$$P_{ti} = \frac{P_{tp} \cdot w_{sit}}{1 - w_{sit}} - P_{clrc},$$ (2.13.)

kur

P_{ti} – tekstilizstrādājumu imports (t/gadā);

P_{tp} – tekstilizstrādājumu ražošana (t);

w_{sit} – importēto tekstilizstrādājumu īpatsvars;

P_{scpa} – slēgtā cikla otrreizēji pārstrādāti apģērbi (t/gadā).

"**Pieejamais apģērbs**" sākotnējo vērtību iegūst, reizinot īpašo apģērbu patēriņu ar iedzīvotāju skaitu un apģērba kalpošanas laiku. Apģērba daudzums tiek reizināts ar kalpošanas laiku, lai iegūtu aptuvenu lietošanai pieejamā apģērba daudzumu. Iznākumu, **apģērba izmešanu**, iegūst, dalot krājuma vērtību ar **apģērba kalpošanas laiku**.

Apģērbu šķirošana balstās uz **sākotnēji šķiroto apģērbu skaitu** un **laika ietekmi uz šķirošanas jaudu**, nevis uz izmesto apģērbu skaitu, jo ES prognozē pastāvīgu šķirošanas pieaugumu neatkarīgi no izmesto apģērbu apjoma. Sākotnējais šķirošanas koeficients tika aprēķināts, reizinot izmestos apģērbus ar 2018. gada šķirošanas koeficientu 38 % [66]. Šķirošanas jauda katru gadu palielinās, pamatojoties uz iepriekšējā gada pieaugumu un prognozēto jaudas pieaugumu. Plānotais tekstilizstrādājumu šķirošanas jaudas pieaugums no 2025. gada ir no 45 līdz 90 000 tonnām gadā [66]. **Sašķirots apģērbs** ir šo divu faktoru summa.

Sistēmas šķirošanas daļā atlikušo parametru vienādojumi ir balstīti uz **šķiroto apģērbu reizinājumu**. **Šķirotā apģērba** plūsmas piedāvājumu iegūst, reizinot atkārtoti lietojamo un nepārdoto apģērbu summu ar **vietēji atkārtoti lietotu apģērbu daļu**. **Pārstrādāta apģērba** plūsma ir vienāda ar parametru "**slēgta cikla pārstrādāts apģērbs**". Sākotnējās krājumu vērtības ir ienākošās plūsmas, kas dalītas ar DT, jo izejošās plūsmas ir krājumi, kas dalīti ar DT, lai izveidotu aizkavi. Ar izejošajām plūsmām saistītie parametri ir tādi paši kā plūsmu vērtības.

Apģērbu daudzums sadzīves atkritumos ir atkarīgs no šķiroto apģērbu daudzuma. Vienādojumā sašķirotais apģērbs tiek atņemts no izmestā apģērba. Parametru vienādojumu pamatā ir reizinājums **Apģērbs sadzīves atkritumos** un dotā attiecība. Papildus šiem parametriem ražošanas un pārdošanas atkritumi tiek pievienoti un reizināti ar daļām. Nepārdoto apģērbu sadalījums pa plūsmām nav zināms, tāpēc pieņemts, ka 40 % tiek sadedzināti, 20 % tiek apglabāti izgāztuvēs, bet pārējais – izmantots atkārtoti.

Zinātniskajā literatūrā vai statistikas datos ir jābūt pieejamai informācijai par to, vai ES apģērbi, kas nonāk sadzīves atkritumos, tiek reģenerēti vai kompostēti. Modelis ietvēra šos parametrus, lai nodrošinātu šādu praksi turpmākajos scenārijos. Dati par apģērbu sadedzināšanas un iznīcināšanas rādītājiem ES nav pieejami, tāpēc izmantoti Amerikas Savienoto Valstu (ASV) dati. ASV 2018. gadā 83 % modes tekstilizstrādājumu tika apglabāti izgāztuvēs un 17 % tika sadedzināti, ietverot enerģijas reģenerāciju [135].

Modelī iekļautais dzīves cikla emisijas koeficients iegūts, dalot ES 2020. gada apģērbu patēriņa SEG emisijas ar tajā gadā patērēto apģērbu daudzumu [65]. Modelī ievietotā vērtība ir 22,53 t CO_2 ekv. uz tonnu apģērba. Turklāt, lai iegūtu emisijas koeficientu katram posmam, tika izmantots procentuālais sadalījums pa dzīves cikla posmiem, kā noteikts literatūras analīzē. Katrā dzīves cikla posmā saražotā, patērētā vai izmestā apģērba daudzums tiek reizināts, lai iegūtu emisijas no katra posma. Visi parametri tiek summēti, lai iegūtu kopējās gada emisijas. Galu galā simulācijas periodā notiek emisiju uzkrāšanās.

Kopējās emisijas iegūtas, izmantojot ražošanas struktūru, jo nebūtu precīzi reizināt patēriņa datus ar SEG emisijas koeficientu. Piemēram, pārprodukcija arī veicina SEG emisijas, jo tiek

saražots vairāk apģērbu, nekā patērēts, un to ražošana, sadedzināšana un iznīcināšana arī rada SEG emisijas.

Modeļa pārbaude

Modeļa pārbaude ir nepieciešama, lai nodrošinātu, ka modelis ir pilnīgs un derīgs. Modelis var būt uzticams tikai daļēji, jo tas nekad pilnībā neatbildīs faktiskajai sistēmai, taču modeli var uzskatīt par uzticamu, ja to var droši izmantot. Modeļa validācija nodrošina modeļa uzticamību. Sistēmdinamikas modeļu pārbaudes testus iedala trīs grupās: modeļa struktūras pārbaudes testi, modeļa uzvedības pārbaudes testi un politikas ietekmes novērtējuma testi [54]. Vispirms tiek novērtēta modeļa struktūra, neņemot vērā elementu savstarpējo saistību, un tikai pēc tam tiek novērtēta modeļa uzvedība. Tika veikti četrpadsmit verifikācijas testi, tostarp struktūras, parametru un robežu atbilstības (strukturālās un uzvedības) pārbaudes testi. Papildu testi ietvēra ekstremālus apstākļus, izmēru konsekvenci, uzvedības reproducēšanu un prognozēšanu, uzvedības anomāliju noteikšanu, pārsteiguma uzvedību, politikas galējības un uzvedības jutīgumu.

Politikas izstrāde

Sistēmdinamikas modeļa politikas veidošana ietver plūsmu regulēšanu, bieži vien izveidojot jaunu atgriezeniskās saites struktūru vai vājinot vai pastiprinot esošās atgriezeniskās saites. Sākotnēji ir jāatrod sviras punkti, kas maina plūsmu un krājumu uzvedību. Ir divpadsmit galvenie sviras punkti, kas tiek sakārtoti pēc to efektivitātes. Piemēram, divpadsmitais ir konstantes, parametri un skaitļi; pirmā ir spēja pārvarēt paradigmas. Divpadsmitā ir vismazāk efektīva, jo šie sviras punkti reti maina uzvedību ilgtermiņā, savukārt pirmais ir visefektīvākais, jo tas var atrauties no esošajām paradigmām un radīt savas unikālās vērtības un prioritātes [136].

Pētījuma [What Drives the Circular Economy? Textile Sorting or Consumtion Reduction] gaitā ir izstrādāti divi politikas instrumenti, kas darbojas divos dažādos sviras punktos. Tā kā sistēma ir vispārīga un samērā liela mēroga, nevis, piemēram, viena tekstila uzņēmuma sistēma, politikas instrumentu mērķis ir parādīt, kuram sviras punktam ir visbūtiskākā ietekme uz sistēmas darbību. Politikas instrumenti nav balstīti uz pašreiz plānotajiem politikas pasākumiem ES.

Pirmais politikas instruments ir **patēriņa samazināšanas politika**. Politikas instrumenta struktūras pamatā ir izaugsme un sabrukums. Sistēma ir parādīta 2.9. attēlā. Augšanas un sabrukšanas uzvedību raksturo struktūra ar krājumu, kam ir ierobežota jauda. Jaudas signāls tiek aizkavēts tā, ka, pārsniedzot jaudu, notiek sabrukums, kam neseko atjaunošanās, jo ir izveidojusies jauna samazināta jauda [137]. Savukārt izstrādātā politikas instrumenta struktūra ir nedaudz pārveidota, jo apģērbu krājumu īpatnējam patēriņam nav ne jaudas, ne maksimālā īpatnējā patēriņa. Politika izstrādāta, lai tā būtu atkarīga no sistēmas radītajām emisijām.
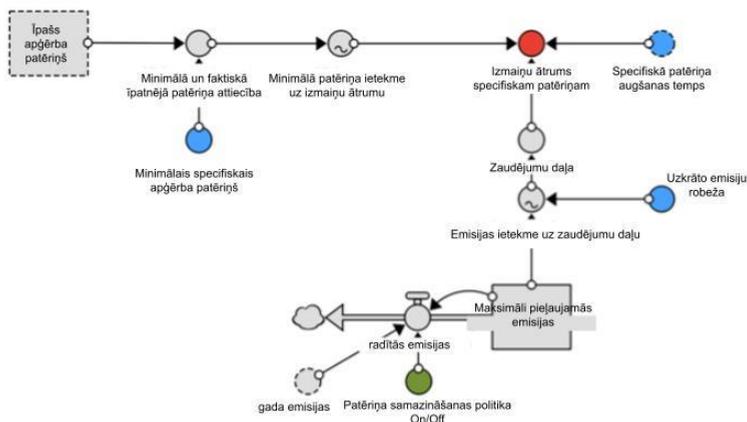
2.9. attēls. Sistēmas E daļa: patēriņa samazināšanas politikas struktūra.

Politikas instruments neatspoguļo politiku praksē. Tomēr tas varētu būt, piemēram, politika sabiedrības izpratnes veicināšanai par vidi, ieviešot ilgtspējības marķējumus/logotipus, jo sistēma ir atkarīga no radītajām emisijām. Tiek noteikts kumulatīvs emisiju ierobežojums, kas ir 1 miljards t CO_2 ekv. Katru gadu radītās emisijas samazina krājuma vērtību. Emisiju **ietekme uz zaudējumu daļu** ir grafisks ietekmes uz zaudējumu daļu attēlojums. Jo mazāk pieļaujamo emisiju paliek, jo lielāka ietekme uz zaudējumu daļu. Zaudējumu daļa tiek atņemta no **īpatnējā patēriņa pieauguma ātruma**, tādējādi samazinot apģērbu īpatnējo patēriņu.

Lai noteiktu jauno krājumu ietilpību, ir pieņemts, ka minimālais īpatnējais patēriņš ir 5 kg apģērba uz vienu iedzīvotāju. Kad krājumu vērtība sāk tuvoties minimālajai jaudai, **minimālā patēriņa ietekme uz izmaiņu ātrumu** tuvojas nullei. Ietekme ir reizinātājs parametrā "**specifiskā patēriņa izmaiņu ātrums**", tāpēc, kad tas sasniedz nulli, arī izmaiņu ātrums ir nulle, un patēriņš nemainās.

Otrs politikas instruments ir **apģērbu šķirošanas politika**. Tas sastāv no divām struktūrām. Pirmā struktūra ir parādīta 2.10. attēlā. Tās pamatā ir informācijas kampaņas struktūra no sistēmdinamikas modeļa, kuras mērķis ir prognozēt atjaunojamās enerģijas potenciālu [138]. Struktūra ir orientēta uz mērķi, iekļaujot informācijas aizkavi ar funkciju *SMTH1*. Šī funkcija veido ievades pirmās kārtas eksponenciālo gludumu. Šīs funkcijas parametram seko efekts, kas normalizē vērtību no 0 līdz 1. Efektu grafiski izsaka ar S formas līkni. Iespējamība un laika aizkave ir iestatīti tā, lai ietekmētu šķirošanas atbalsta palielināšanu vai samazināšanos.
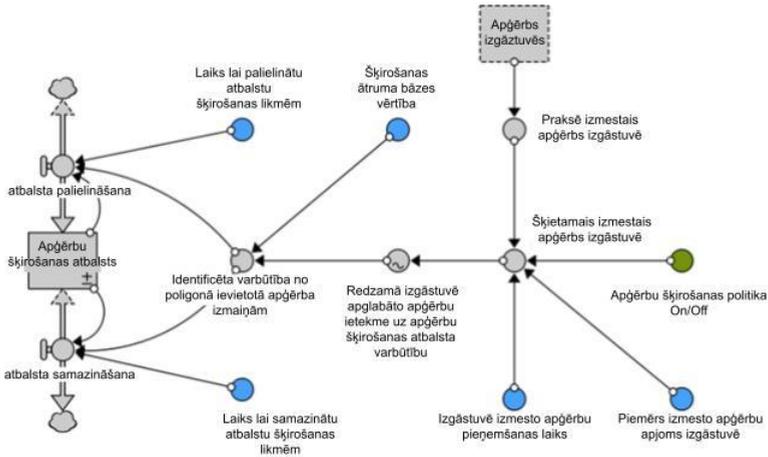
2.10. attēls. Sistēmas E daļa: apģērbu šķirošanas politikas atbalsta struktūra.

Šī politikas instrumenta struktūra nosaka politiskā atbalsta intensitāti. Tā kā politikas instruments nav balstīts praktiskajā politikā, šis atbalsts var būt jebkāda veida, piemēram, informatīvs un finansiāls atbalsts atkritumu apsaimniekošanas uzņēmumiem. Pamatvērtība šķirošanas ātrumam un atsauces vērtība apģērbu pārstrādes ātrumam ir no 2023. gada, jo tiek pieņemts, ka politikas veidotāju datu iegūšanas laiks ir divi gadi. Paredzams, ka atbalsta palielināšanas vai samazināšanas laiks ir trīs gadi.

Lai politikas instruments būtu praktiskāks, ieviesta papildu struktūra, paredzot pietiekamas šķirošanas jaudas ieviešanu, lai sasniegtu vēlamo šķirošanas ātrumu. 2.11. attēls ilustrē šo struktūru, kuras pamatā ir bioekonomikas modeļa kapacitātes struktūra [139]. Bioekonomikas sistēmas ražošanas jauda ir atkarīga no pieejamajiem resursiem, un šajā gadījumā tas ir izmests apģērbs. Tomēr to ierobežo **apģērbu šķirošanas atbalsts**, jo sniegtais atbalsts var nebūt pietiekams, lai sakārtotu visas izmestās drēbes. Laika parametri tika pieņemti, jo netika veikta padziļināta literatūras analīze par apģērbu šķirošanu. Modelī jaudas regulēšana ilgst divus gadus, uzstādīšanai vajadzīgi trīs gadi. **Ekspluatācijas jaudas** krājumam ievadplūsma tika pievienota, pamatojoties uz plānoto jaudas pieaugumu katru gadu, pirms politikas instruments sāk darboties. 2025. gadā, kad politikas instruments sāks darboties, **praksē šķirots apģērbs** aizstās **šķiroto apģērbu**.

2.11. attēls. Sistēmas F daļa: apģērbu šķirošanas politikas jaudas uzstādīšanas struktūra.

Sankey **diagrammas**

Sankey diagramma ir sistēmas saišu, attiecību un daudzumu vizuāls attēlojums, tāpēc tā var koncentrēt lasītāja uzmanību uz būtiskāko, vienlaikus saglabājot sistēmu vienkāršu [140]. Šo metodi var izmantot, lai vienkāršotu un samazinātu sistēmu sarežģītību. Šajā pētījumā lielākā daļa sistēmas parametru ir plūsmas, tāpēc tika izveidotas *Sankey* diagrammas, lai padarītu rezultātus lasāmākus. Slēgtās saites, piemēram, atkārtoti izmantoto apģērbu ievade no pārdošanas pārpalikumiem atpakaļ apģērbu mazumtirdzniecībā, diagrammās netika parādītas, bet tika parādītas kā jaunas plūsmas. Diagrammu izveidošanai izmantots tiešsaistes rīks *SankeyMATIC.*

2.5. Izplūdusī kognitīvā karte (*FCM*)

Kvalitatīvo sistēmu analīzi jeb kvalitatīvo modelēšanu arvien vairāk izmanto, lai analizētu sarežģītu sistēmdinamiku. B. Kosko ieviesa izplūdušās kognitīvās kartes (*FCM*) kā rīku dinamiskai kvalitatīvo sistēmu uzvedības uztverei un skaidrošanai. *FCM* arvien vairāk izmanto, lai modelētu un analizētu kvalitatīvo sistēmu uzvedību. Pēdējo 30 gadu laikā šī pieeja ir kļuvusi arvien populārāka, pateicoties vienkāršajam dizainam un zemajām skaitļošanas prasībām. Lai modelētu sociālo sistēmdinamiku, galvenokārt izmanto divas pieejas – deduktīvo un induktīvo. Deduktīvajā pieejā izmanto zināšanas, kas iegūtas, intervējot attiecīgās jomas ekspertus, savukārt induktīvā pieeja ir automatizēta un daļēji automatizēta pieeja, kas paredzēta *FCM* noteikumu izpētei pamatojoties uz vēsturiskajiem datiem [141], [142], [143], [144].

Kopumā *FCM* ir vairākas priekšrocības salīdzinājumā ar tradicionālajām kvantitatīvas modelēšanas pieejām. *FCM* priekšrocības ietver, piemēram, spēju modelēt datus ierobežotās vidēs, izmantojot dabisko valodu, izteikt zināšanas, uztveri, pieredzi vai uzskatus, kā tos formulējis eksperts vai ieinteresētā persona, bieži ar neskaidru informāciju. Turklāt *FCM* rezultātus ir viegli interpretēt gan speciālistiem, gan sabiedrībai. Tomēr, ja tos izmanto kvalitatīvas sistēmdinamikas uzvedības modelēšanai, tradicionālajam *FCM* ir arī vairāki trūkumi. Šie trūkumi lielā mērā ir saistīti ar nepilnīgu:

1) cēloņsakarības semantiku un ierobežotu cēloņsakarības dinamiku uztveri, attēlošanu un simulāciju;
2) laika attiecību iekļaušanu;
3) difūzijas noteikšanu, attēlošanu un simulāciju;
4) dinamikas simulāciju, izmantojot vienas slāņa perceptrona mehānismus.

Lai pārvarētu šos trūkumus, ir izstrādāti vairāki *FCM* paplašinājumi, taču lielākā daļa izstrādāto paplašinājumu mēģina risināt specifiskas problēmas ar tradicionālo *FCM* un nemēģina risināt problēmas, kas saistītas ar *FCM* dinamikas modelēšanu [14]–[16].

FCM sastāv no jēdzieniem (lingvistiskiem terminiem), kas tiek izteikti ar mezgliem. Virzītas bultas ar skalām izskaidro attiecības starp jēdzieniem. Šie svarīgumi apraksta cēloņsakarības stiprumu ar {−1,0} un {0,1}, kas attiecīgi norāda uz cēloņsakarības samazināšanos un palielināšanos. Jēdzieni un to savstarpējās attiecības tiek attēlotas ar mezgliem, un virzītas bultas ar to svarīgumu izskaidro konkrētas sistēmas izkārtojumu. Tas tiek attēlots matricā, kas ļauj veikt standarta algebriskās operācijas, lai atrastu attiecības starp mezgliem. Kosko ieviestās *FCM* [10] tiek simulētas, izmantojot matemātisko formulu, kas izteikta 2.14. vienādojumā:

$$C_j\left(t+1\right) = f\left(\sum_{i=1, i \neq j}^{n} W_{ij} \cdot C_i\left(t\right)\right), \tag{2.14.}$$

kur

n – konceptu daudzums;

$C_j(t+1)$ – koncepta vērtība nākamajā iterācijā;

$C_i(t)$ – koncepta vērtība iterācijas laikā;

W_{ij} – reciprocitātes svarīgums starp cēloni un ietekmi.

Tad tiek kartēts uz iepriekš noteiktu diskursa visumu, izmantojot transformācijas funkcijas. Visbiežāk sastopamās ir sigmoīda un hiperboliskās transformācijas funkcijas rezultāti *FCM* saistībā ar modelēšanu un simulāciju.

Ideālā gadījumā, modelējot sarežģītu kvalitatīvu sistēmdinamiku, vajadzētu pielietot *FCM* un spēt uztvert un modelēt cēloņsakarības dinamiku. FCM ietver noteiktu cēloņsakarības dinamiku īpašību integrāciju un uztveršanu, kas var ietvert, bet neaprobežojas ar šādiem:

- cēlonis var izpausties dažādos apstākļos vai dažādos veidos;
- cēlonis nevar būt divi stāvokļi vai stiprības piemērs laikā (divi stāvokļi ir iespējami tikai kvantu superpozīcijā);

- cēlonis ir pirms sekām, tāpēc laika atkarība ir raksturīga;
- cēloņa ietekmei jāpalielinās vai jāsamazinās;
- cēlonis noteiktā stāvoklī var radīt sekas, kas rodas dinamiskās laika nobīdes, laika aizkaves vai laika samazināšanas rezultātā;
- cēlonis var radīt sekas, kas ir dinamiskas pozīcijas vai spēka izmaiņu rezultātā (t. i., tās var būt nelineāras, nemonotoniskas un asimetriskas);
- efekts ir jūtams tikai tad, kad mainās procesa stāvoklis vai spēks;
- ietekme var būt relatīvu cēloņu rezultāts.

Turklāt parastās *FCM* un vairākus vienkāršā slāņa perceptrona rezultātus izmanto, lai modelētu un izskaidrotu kvalitātes sistēmdinamiku kā universālu notikumu. Tomēr sistēmdinamikas cēloņsakarība var būt nosacīta, iespējama vai ticama. Labākajā gadījumā *FCM* atspoguļo arī fragmentētu zināšanu nenoteiktību un neprecizitāti. Šo neprecizitāti var attēlot un simulēt, izmantojot izplūdušās sistēmas un *FCM*, kā to paredzēja Kosko [145]; viņa pieeja ir izplūdušās loģikas un mākslīgo neironu tīklu kombinācija.

Metodes lietošana bioproduktu novērtēšanai

FCM modelēšanas metode pētījumā izmantota, lai salīdzinātu dažādas ražošanas procesu metodes. Tā palīdzēs saprast, kura no metodēm vislabāk atbilst ilgtspējības kritērijiem, identificēt potenciālos šķēršļus, lai iegūtu uzticamus un objektīvus rezultātus, un noskaidrot, vai šāda veida integrētās analīzes izmantošana ir piemērota, lai salīdzinātu dažādas pētījumā aplūkotās ražošanas procesu alternatīvas. *FCM* modelēšana ir secīgs darbību kopums, kas nodrošinās, ka pētījuma mērķis tiek sasniegts caurspīdīgā un saprotamā veidā, lai analizētu sešpadsmit ražošanas procesus.

Lai salīdzinātu visus aprakstītos ražošanas procesus, ir jādefinē vissvarīgākie kritēriji. Šajā procesā tiek izmantoti vairāki kritēriji, padarot izvēles efektīvākas, racionālākas un skaidrākas. Analīzes mērķis ir strukturēt procesus, lai definētu mērķus, novērtētu iespējamos alternatīvas un salīdzinātu tās no dažādām perspektīvām. Izvērtējot prioritāros kritērijus, tika izvēlēti šādi kritēriji:

- vides aspekti;
- tehnoloģiskie aspekti;
- ekonomiskie aspekti;
- sociālie aspekti.

Vides aspekti	Ekonomiskie aspekti	Sociālie aspekti	Tehnoloģiskie aspekti
Resursu pieejamība	Inovācijas	Jaunu darba vietu skaits	Tehnoloģiskās sarežģītības pakāpe
Atkritumu samazināšana	Ekspluatācijas izmaksas	Sociālie aspekti	Tehnoloģisko iekārtu pieejamība
Ietekmes uz klimata pārmaiņām samazināšana	Atmaksāšanās laiks	Ietekmes uz klimata pārmaiņām samazināšana	Tehnoloģijām izmantota platība
Emisiju samazināšana	Lietderība	Trokšņa līmenis	Tehnoloģiskā risinājuma ražošanas jauda

2.12. attēls. Novērtēto kritēriju aspekti.

Ņemot vērā informācijas pieejamības, ilgtspējības un lietderības ierobežojumus, modelēšanai ir izvēlēti bioekonomikas skatupunkta rādītāji.

Visi izvēlētie kritēriji un apakškritēriji ir kvalitatīvi, tāpēc tiem jāpiešķir skaitliskās vērtības, pamatojoties uz pētījumā veikto ražošanas procesu analīzi. Kvalitatīvā raksturojuma pieeja, atšķirībā no kvantitatīvo rezultātu pieejas, padara metodoloģijas apstiprināšanas daļā iegūtos rezultātus subjektīvākus. Tomēr, ja būtu pieejami precīzi kvantitatīvie dati par procesiem, skatījums uz lietderības veiktspēju būtu ierobežots.

Katrs apakškritērijs tiks novērtēts ar vērtību no –1 līdz 1, kur 1 norāda uz stiprāko saiti un tas norādīs uz labāko, stiprāko iespējamo saiti no bioekonomikas un lietderības skatupunkta. Apakškritērijā iegūtā vērtējuma saite ir salīdzināma ar augstāko ieviešanas efektivitāti. Savukārt zemākais vērtējums -1 norāda uz vājāko saiti vai rezultātu no bioekonomikas un lietderības skatupunkta.

Metodoloģijas aprobācija

Pētījuma rezultātu alternatīvas ir 16 bioprodukti. Šīs alternatīvas tiek novērtētas ar *FCM* metodi, izmantojot *Mental Modeler* rīku, saskaņā ar četriem kritērijiem: vides, ekonomiskajiem, sociālajiem un tehnoloģiskajiem. Šie galvenie kritēriji tiek konsolidēti 16 apakškritērijos, un katra alternatīva tiek novērtēta skalā no –1 līdz 1, kur -1 ir vājākā saite (sliktākā) un 1 ir stiprākā (labākā).

Kritēriju un apakškritēriju savstarpējā saistība

2.12. attēls apkopo analizējamo vides, tehnoloģisko, ekonomisko un sociālo aspektu novērtējumus. Vides aspekti ilustrē mijiedarbību starp resursu pieejamību, atkritumu samazināšanu, ietekmes uz klimata pārmaiņām samazināšanu un emisiju samazināšanu. Piemēram, atkritumu un emisiju samazināšana negatīvi ietekmē resursu pieejamību, jo daļu no

atkritumiem (blakusproduktiem) un emisijām var izmantot kā izejvielu citam ražošanas procesam. Savukārt atkritumu samazināšana ar spēcīgu pozitīvu saiti tieši pozitīvi ietekmē vidi, jo samazina piesārņojumu un tādējādi ražošanas procesos rodas mazāk atkritumu vai tie nerodas vispār. No šī skatupunkta ir aplūkotas visu apakšaspektu mijiedarbības, kas kopā veido vienu no četriem aspektiem. Vizuāli var redzēt zilu saiti, kurai ir pozitīva vērtība no 1 līdz 0, un brūnu saiti, kuras vērtība ir no 0 līdz –1. Jo biezāka ir krāsa, jo lielāka ir tās pozitīvā vai negatīvā vērtība.
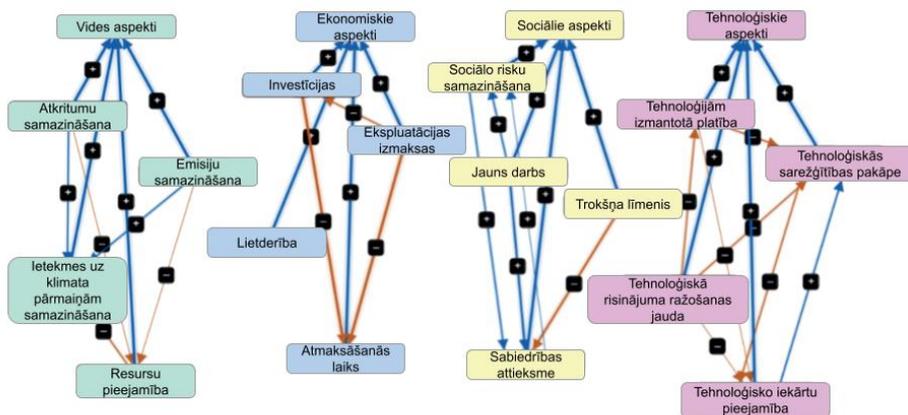
2.13. attēls. Saiknes starp visiem četriem aspektiem un to apakškritērijiem.

Lai turpinātu modeļa veidošanu, izmantotas iepriekš aprakstītās aspektu saites un papildinātas ar katra no 16 ražošanas procesu nosaukumu blokiem un tādu pašu ražošanas procesa lietderības bloku, kas nepieciešams, lai modelēšanas rīks varētu aprēķināt kopējo rezultātu konkrētam ražošanas procesam.

Metodoloģijas aprobācija citronskābes ražošanas procesam

Visi 16 ražošanas procesi ir analizēti un modelēti pētījumā [Bioeconomy Towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps], tomēr viens no ražošanas procesiem tiks detalizēti parādīts šajā pētījumā, bet pārējo 15 ražošanas procesu rezultāti tiks novērtēti arī rezultātu un diskusiju sadaļā, jo struktūra un pieeja ir analoģiska visiem ražošanas procesu modeļiem.
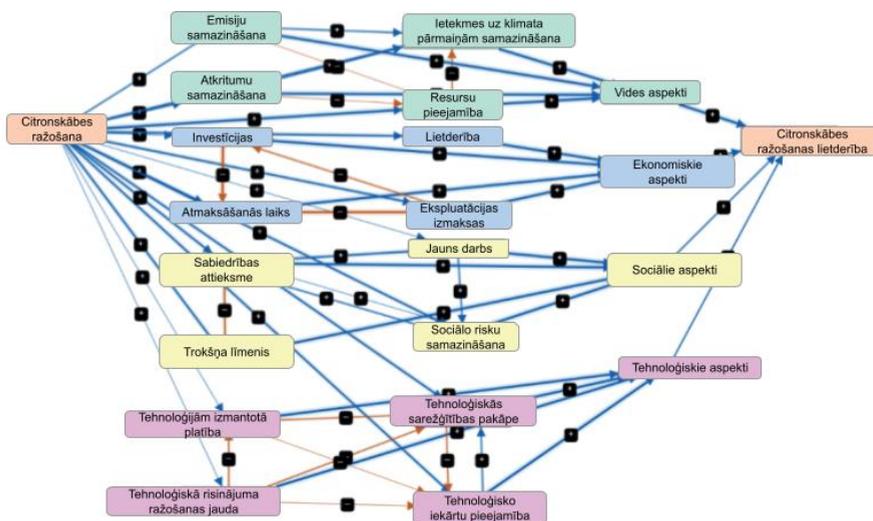
2.14. attēls. Uzlabots citronskābes ražošanas procesu vizualizācijas modelis.

Lai modeļa vizualizāciju būtu vieglāk saprast, vides aspektu grupa ir iekrāsota zaļā krāsā, ekonomiskie aspekti – zilā krāsā, sociālie aspekti – dzeltenā krāsā, bet tehnoloģiskie aspekti – purpursarkanā krāsā. Savukārt konkrētā mainīgā ražošanas procesa nosaukums un tā lietderības bloks ir iekrāsoti oranžā krāsā.

Katram ražošanas procesam izveidotas saites katram no apakškritērijiem, norādot saites stiprumu diapazonā no -1 līdz 1, pamatojoties uz ekspertu vērtējumu. Piemēram, citronskābes ražošanas atmaksāšanās laiks ir salīdzinoši īss, tāpēc šai saitei ir pozitīva vērtība 0,7. Tikmēr tehnoloģijai nepieciešamā platība ir aptuveni 1 ha, kas tiek novērtēta ar 0,1 pozitīvu vērtību.

Pabeidzot modeļa vizualizācijas daļu, katrai modeļa pozīcijai var iegūt kvantitatīvu rezultātu. Iegūtās vērtības ir parādītas 2.7. tabulā.

Citronskābes ražošanas procesa kvantitatīvās vērtības

Komponents	Iekšējais leņķis	Ārējais leņķis	Centralitāte
Citronskābe	0	6,949	6,949
Vides aspekti	4	1	5
Tehnoloģiskie aspekti	4	0,48	4,48
Sociālie aspekti	4	0,2	4,2
Ekonomiskie aspekti	4	0,81	4,810
Atkritumi samazināšana	0,47	1400	1,87
Resursu pieejamība	1,23	1,19	2,42
Ietekmes uz klimata pārmaiņām samazināšana	1,21	1	2,21
Emisiju samazināšana	0,48	1,339	1,819
Atmaksāšanās laiks	2,5	1	3,5
Lietderība	0,52	1	3,5
Ekspluatācijas izmaksas	0,5	2,31	2,81
Investīcijas	0,42	2	2,42
Sociālo risku samazināšana	1,02	1,25	2,27
Trokšņa līmenis	0,52	1,58	2,1
Sabiedrības attieksme	2,08	1,16	3,24
Jaunu darba vietu daudzums	0,09	2,09	2,179
Tehnoloģiskā risinājuma ražošanas jauda	0,09	1,680	1,770
Tehnoloģiskās sarežģītības pakāpe	1,44	1,28	2,7199
Tehnoloģijām izmantotā platība	0,42	1,28	1,7
Tehnoloģisko iekārtu pieejamība	0,960	1,44	2,4
Citronskābes ražošanas lietderība	2,49	0	2,49

Aspektu un apakškritēriju tabula ar iegūtajām vērtībām ir sakārtota pēc centrālā lieluma, t. i., pozitīvo un negatīvo saišu kopskaita, kas parāda visietekmīgākos aspektus un apakškritērijus. No tabulā iegūtajām vērtībām var secināt, ka no bioekonomikas viedokļa visietekmīgākais citronskābes ražošanas procesa aspekts ir vides aspekts, kam seko ekonomiskais aspekts. Tādā veidā katru ražošanas procesu var pārskatīt, un iespējamo ražošanas procesu var izvēlēties atbilstoši jebkuram no piedāvātajiem aspektiem. Protams, strādājot ar modeli, ir iespējams mainīt un skatīt iegūtos rezultātus, prioritizējot sociālo aspektu vai jebkuru citu nepieciešamo prioritāti.

Kad katram apakškritērijam ir iegūtas kvantitatīvās vērtības, *Mental Modeler* rīkam ir iespēja pāriet uz rezultātu sadaļu. Galvenais mērķis ir iegūt efektīvus ražošanas procesa rezultātus, kas būs diapazonā no 0 līdz 1.
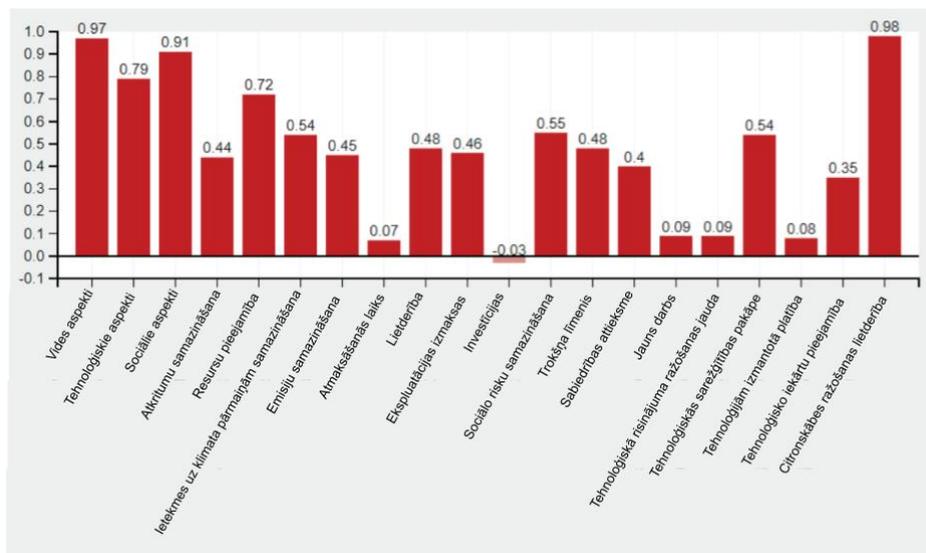
2.15. attēls. Citronskābes ražošanas procesa rezultāti.

2.15. attēlā redzams galvenais secinājums par citronskābes ražošanas procesu, proti, citronskābes ražošanas efektivitāte ir 0,97. Visi darbā aprakstītie ražošanas procesi tiks salīdzināti ar šo galapunktu. Kā redzams grafikā, citronskābes ražošanas process vislielāko ieguldījumu sniedz vides un sociālajos aspektos, bet vājākās vietas šādas rūpnīcas izveidē būtu saistītas ar investīcijām un atmaksāšanos. Tas ir saistīts ar lielu nepieciešamo rūpniecisko iekārtu un tehnoloģiju uzstādīšanu, iegūstot salīdzinoši mazu ražošanas jaudu. Ņemot vērā, ka pētījums ir vērsts uz ilgtspējību, lai sasniegtu ES Zaļā kursa mērķus, citronskābes ražošanas procesa lietderība ir ļoti augsta – 0,97. Ja modelēšanas fokuss būtu tikai uz ekonomiskajiem aspektiem, šī ražošanas procesa rezultāts būtu mazāk pozitīvs. Tāpēc tika meklēts veids, kā modelēt arī prioritāšu izmaiņas.

Veidojot modeli, *Mental Modeler* rīks nodrošina arī iespēju ietekmēt un mainīt prioritātes rezultātu un scenāriju bloku sadaļā. 18. attēlā parādīti rezultāti, kad vides aspekti tiek samazināti līdz -0,49 un ekonomiskie aspekti palielināti līdz 1. Tādējādi tiek simulēta situācija, kurā potenciālais investors vēlas novērtēt, vai citronskābes ražošanas process ir ekonomiski dzīvotspējīgs, bet vides aspekti šķiet mazāk svarīgi. Šādā situācijā aplūkotais scenārijs parāda lietderības vērtību 0,71, kas arī ir nozīmīga pozitīva vērtība un būtu salīdzināma ar citām alternatīvām.
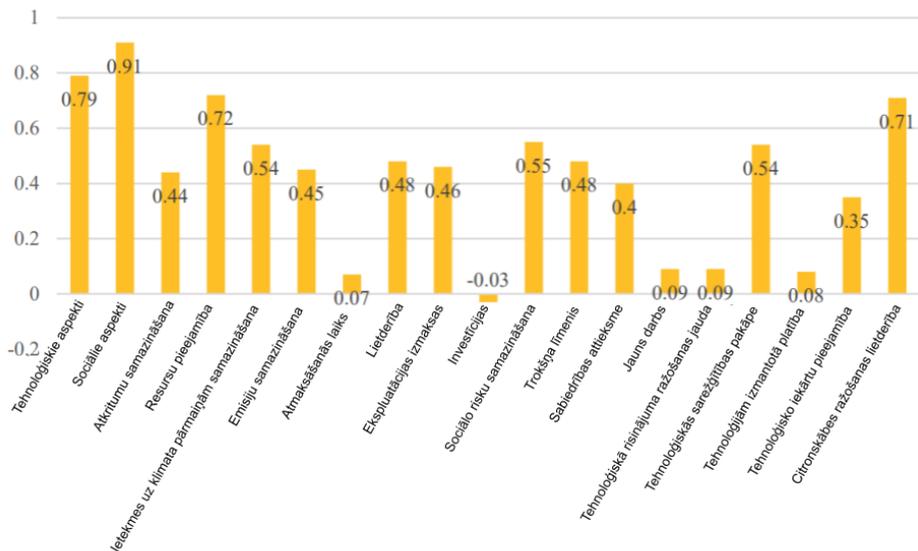
2.16. attēls. Citronskābes ražošanas procesa rezultāti ar paaugstinātu ekonomisko vērtību.

Tādējādi šāds projekts ir ne tikai videi draudzīgs, bet arī ekonomiski dzīvotspējīgs, un investors vai potenciālais izstrādātājs var novērtēt alternatīvus ražošanas procesus no dažādiem skatpunktiem un salīdzināt tos ar līdzīgiem kritērijiem.

3. REZULTĀTU APKOPOJUMS

3.1. Daudzkriteriju lēmumu pieņemšanas metode (*MCDA*)

3.1.1. Tekstilmateriālu aprites potenciāla analīzes piemērs [75]

Ievaddati

Attiecībā uz rezultātiem, pēc daudzkritēriju lēmumu pieņemšanas metodes pielietojuma tekstilmateriālu aprites potenciāla analīzes piemērā, ir nozīmīgi skaidri definēt ievaddatus. Visi no literatūras apskata iegūtie ievaddati ir parādīti 3.1. tabulā. Tajā apkopoto vērtību avoti ir uzskaitīti turpmākajās apakšnodaļās.

3.1. tabula.

TOPSIS analīzes ievaddati

Kritēriji	Alternatīvas		
	Modes tekstils	Mājas tekstils	Tehniskais tekstils
Ietekme uz vidi, kg CO_2 ekv kg^{-1}	30,42	5,06	81,45
Mazgāšana, laiki	30	68	63
Paredzamais kalpošanas laiks, gadi	3,13	4,06	6,13
Poligonos apglabātie atkritumi, %	70	68	78
Pārstrādātie atkritumi, %	13	16	5
Auduma izcelsme, %	60	70	80
Tirgus pieprasījums, miljardi EUR	511,39	103,31	177,53
Ražošanas apjoms, %	41	14	17
Starptautiskā tirdzniecība, %	59	2	14
Darba ražīgums, tūkstoši EUR	22	29	47
Pievienotā vērtība, %	1,01	0,28	0,37
Ražošanas tehnoloģiju energoefektivitāte, %	54	70	59
Inovācijas spēja, patenti	5001	127	3440
Nodarbinātība, %	72	16	12
Uzņēmumi, %	75	16	9

Ietekme uz vidi

Galvenais informācijas avots par modes tekstilizstrādājumiem bija *Gonçalves A.* un *Silva C.* pārskata pētījums [51]. Viņi apkopoja dažādu apģērbu ietekmi uz vidi. Analīzei tika izvēlēta jaka, T-krekls un četru veidu džemperi. Tika ņemts vērā tikai lietošanas posms un aprites cikla beigas. Jakas svars ir 0,9 kg, un tās globālās sasilšanas potenciāls (GSP) ir 25,3 kg CO_2 ekv. uz funkcionālo vienību [146]. Tādējādi 1 kg jaku GSP ir 28,1 kg CO_2 ekv. T-kreklu kategorijai GSP ir 5,3 kg CO2 eq kg^{-1} t-kreklu. Tika izmantoti dati par četru veidu džemperiem: vilnas,

kokvilnas, maisījuma un akrila [147]. Vidējais GSP ir 57,9 kg CO_2 ekv kg^{-1} džemperu. Kopumā TOPSIS analīzē tika izmantota vidējā vērtība.

Attiecībā uz mājas tekstilizstrādājumiem izvēlēts astoņu gultasveļu ACN pētījums [17]. Lielākā gultasveļa bija kokvilnas, bet viena bija poliestera un kokvilnas maisījums. Tekstilizstrādājumi atšķīrās pēc kopšanas veidaun krāsu toņiem. Aprēķinātais vidējais GSP gultasveļai bija 4,2 kg CO_2 ekv., un katra parauga virsmas svars bija aptuveni 115 g m^{-2} un virsma 7,2 m^2. Tādējādi parauga svars bija 0,8 kg, un GSP 1 kg gultasveļas ir 5,1 kg CO_2 ekv. Tika aplūkots gandrīz viss aprites cikls, izņemot aprites cikla beigas.

Pētījumā izvēlētie tehniskie tekstilizstrādājumi: ar antipirēnu (*FR*) apstrādāta vilna un ar sudraba nanodaļiņām (AgNPs) apstrādāti poliestera aizkari. Šo izstrādājumu ACN pētījumā aplūkota tikai lietošanas fāze un aprites cikla beigas [3]. Tāpēc modes tekstilizstrādājumiem aplūkoti tādi paši aprites posmi. Ar *FR* apstrādātiem vilnas aizkariem vidējais GSP lietošanas posmā ir 32 kg CO_2 ekv kg^{-1}. Ar AgNPs apstrādātu poliestera aizkaru vidējais GSP lietošanas posmā ir četras reizes lielāks, jo šim izstrādājumam ir nepieciešams četras reizes vairāk mazgāšanas. Ar *FR* apstrādātas vilnas un ar AgNPs apstrādātu poliestera aizkaru GSP aprites beigu posmā ir attiecīgi 1,1 kg CO_2 ekv. kg^{-1} un 0,8 kg CO_2 ekv. kg^{-1}.

Šie dati ir iegūti no uzticamiem pētījumiem, taču jāatzīmē, ka pastāv dažādas nepilnības salīdzināšanas procesā. Piemēram, tehniskajam un modes tekstilmateriālam tika ņemta vērā aprites cikla beigu un lietošanas fāze, bet mājas tekstilizstrādājumiem tika ņemts vērā gandrīz viss aprites cikls. Arī ACN iegūtie dati ir atkarīgi no izstrādājumā izmantotā materiāla, valsts, kurā iegūtas izejvielas, kā arī no tā, kur notika ražošanas un lietošanas posms. Lai ņemtu vērā dažādu audumu veidu ietekmi uz vidi, izmantota vairāku izstrādājumu vidējā GSP vērtība.

Mazgāšana

Tekstilizstrādājumu vidējais mazgāšanas laiks ņemts no ACN pētījumiem. Jaka paredzēta desmit mazgāšanas reizēm [146], bet T krekla kalpošanas laiks ir aptuveni 52 mazgāšanas reizes [84]. Džemperiem tas ir 28 mazgāšanas reizes [147]. Vidējais astoņu gultasveļu mazgāšanas reižu skaits ir 68 [17]. Ar *FR* apstrādātos vilnas aizkarus to kalpošanas laikā paredzēts mazgāt 25 reizes, un ar AgNPs apstrādātos poliestera aizkarus var mazgāt četras reizes biežāk [3].

Paredzamais kalpošanas laiks

Modes un mājas tekstilizstrādājumu paredzamais kalpošanas laiks ņemts no Starptautiskās patēriņa tekstilizstrādājumu taisnīguma prasību rokasgrāmatas [83]. Apģērbu vidējais kalpošanas laiks ir 3,13 gadi. Mājas tekstilizstrādājumu vidējais kalpošanas laiks ir 4,06 gadi. Daži tekstilizstrādājumi tika izslēgti no vidējās vērtības aprēķiniem, jo tie neietilpa šī pētījuma jomā. Lai pārliecinātos, ka rādītāji vairāk vai mazāk atbilst realitātei, tie salīdzināti ar datiem no citiem literatūras avotiem. Apvienotajā Karalistē veiktā pircēju aptauja parāda, ka apģērba vidējais aktīvās lietošanas laiks ir 3,3 gadi [68]. Gultasveļu mazgā divas reizes mēnesī, un tā kalpo līdz 60 mazgāšanas reizēm [17], kas nozīmē, ka tās kalpošanas laiks ir 2,5 gadi. Tas atbilst gultas pārklāju, palagu un spilvendrānu kalpošanasilguma rādītājiem [83].

Zinātniskajā literatūrā nebija pieejami dati par tehnisko tekstilizstrādājumu kalpošanas ilgumu, tāpēc dati iegūti no uzņēmumu un emuāru īmekļa lapām. Ugunsizturīga darba apģērba

kalpošanas laiks ir no viena līdz četriem gadiem atkarībā no izmantotā tekstilmateriāla [148]. Necauršaujamu vestu paredzamais kalpošanas laiks ir pieci gadi [149]. Labas kvalitātes komerciālās teltis kalpo līdz 10 gadiem [150]. Ar pūkām un sintētisko vati pildītu guļammaisu kalpošanas laiks ir attiecīgi desmit un trīs līdz četri gadi [151]. Vidējā vērtība aprēķināta, pamatojoties uz iepriekš minētajiem datiem.

Poligonā apglabātie atkritumi un pārstrādātie atkritumi

Poligonā apglābāto atkritumi un pārstrādāto atkritumu rādītāju datu avots bija Amerikas Savienoto Valstu Vides aizsardzības aģentūras tīmekļa vietne [135]. Tajā ir konkrēta informācija par divām šim pētījumam būtiskām grupām: apģērbu un apaviem, dvieļiem, gultasveļu un spilvendrānām. Dati parāda, ka gadā saražots 12 970 t modes tekstilizstrādājumu, no kuriem 9070 t noglabātas poligonos, un tikai 1690 t pārstrādātas. Līdzīgi rādītāji ir arī attiecībā uz mājas tekstilizstrādājumiem: saražoti – 1520 t, poligonos noglabāti – 1030 t, bet pārstrādāti – 240 t.

Nebija informācijas par tehnisko tekstilmateriālu plūsmu, tāpēc izdarīti pieņēmumi, pamatojoties uz datiem par modes un mājas tekstilizstrādājumiem [135]. Abos gadījumos aptuveni 17 % tiek sadedzināti, tāpēc tāda pati attiecība pieņemta attiecībā uz tehnisko tekstilu. Tehniskajam tekstilmateriālam, piemēram, aizsargtekstilam, ko izmanto tādās jomās kā veselības aprūpe, ugunsdzēsība, tiesībaizsardzība un ražošana, nepieciešama sarežģīta pārstrāde [3]. Tādējādi pieņemts, ka tehniskie tekstilizstrādājumi tiek pārstrādāti gandrīz trīs reizes mazāk nekā apģērbi un mājas tekstilizstrādājumi.

Auduma izcelsme

Aptuveni 60 % šķiedru, ko izmanto modes tekstilizstrādājumos, ir sintētiskas [86]. No šiem sintētiskajiem materiāliem visplašāk izmanto poliesteri. Mājas tekstilizstrādājumu grupā izmanto vēl vairāk sintētisko materiālu – aptuveni 70 % [86]. Poliestera īpatsvars ir 28 %, bet neilona – 23 %. Tehniskajos tekstilizstrādājumos sintētisko šķiedru īpatsvars ir līdzīgs, bet konkrēti dati nav pieejami. Pieņemts, ka lielāko daļu sintētisko šķiedru izmanto tehnisko tekstilizstrādājumu ražošanā. Tādējādi starpība starp abām tekstilizstrādājumu grupām tika pieskaitīta lielākajai attiecībai.

Tirgus pieprasījums

Visi dati par tirgus pieprasījuma kritēriju ir salīdzināmi, jo tika izmantots tas pats bāzes gads. Pasaules apģērbu tirgus 2021. gadā bija 511,39 miljardi EUR [152]. Pasaules mājas tekstilizstrādājumu un tehnisko tekstilizstrādājumu tirgus tika novērtēts attiecīgi 103,31 miljarda EUR un 177,53 miljardu EUR apmērā [153], [154].

Ražošanas apjoms

Apģērbu ražošana ir vadošā tekstilizstrādājumu ražošanas nozare, tomēr tehnisko tekstilizstrādājumu ražošana ir strauji augoša nozare. ES 27 dalībvalstīs apģērbu ražošana 2021.gadā veidoja 31 %, trikotāžas izstrādājumu – 6 %, bet apakšveļas – 4 %. Šīs izstrādājumu grupas uzskata par modes tekstilizstrādājumiem. Darba apģērbu ražošana netika ņemta vērā, jo

tā var būt gan modes, gan tehniskais tekstils. Mājas un tehnisko tekstilizstrādājumu ražošanas īpatsvars 2021. gadā bija attiecīgi 14 % un 17 % [155].

Starptautiskā tirdzniecība

Šim rādītājam atlasīti tikai dati par ES [155]. 2021. gadā eksportētie sieviešu apģērbi veidoja 24 %, vīriešu apģērbi – 12 %, bet citi trikotāžas un austi apģērbi – 23 %. Mājas un tehnisko tekstilizstrādājumu eksporta īpatsvars bija attiecīgi 2 % un 14 %. Jāatzīmē, ka citās valstīs vai ekonomiskajās savienībās šie rādītāji var atšķirties un ietekmēt kopējos rezultātus [155].

Darba ražīgums un pievienotā vērtība

Darba ražīguma datu iegūšanai tika izmantoti Eiropas Komisijas dati par 2018. gadu [87], jo globālie dati nav pieejami. Kopējā pievienotā vērtība tekstilizstrādājumiem un aksesuāriem, tehniskajiem un rūpnieciskajiem tekstilizstrādājumiem un mājas tekstilizstrādājumiem 2018. gadā bija attiecīgi 19 586, 7121 un 5507 miljoni EUR. Darba ražīgums modes tekstilizstrādājumu nozarē 2018. gadā bija 22 tūkstoši EUR uz vienu nodarbināto. Šī vērtība ir par 14 % lielāka nekā 2015. gadā. Mājsaimniecības tekstilizstrādājumu nozarē darba ražīgums kopš 2015. gada samazinājies par 2 %, bet joprojām bija lielāks nekā modes tekstilizstrādājumu nozarē – 29 tūkstoši EUR uz vienu nodarbināto. Tehniskā tekstila darba ražīgums laika posmā no 2015. līdz 2019. gadam palielinājās par 5 % un vairāk nekā divas reizes pārsniedza modes tekstilizstrādājumu nozari – 47 tūkstoši EUR uz vienu nodarbināto [87].

Otrajam kritērijam tika atlasīti dati par tekstilizstrādājumu pievienotās vērtības īpatsvaru salīdzinājumā ar kopējo ES-27 apstrādes rūpniecības nozari 2018. gadā. Tekstilpreču un aksesuāru, mājas tekstilizstrādājumu un tehnisko un rūpniecisko tekstilizstrādājumu pievienotās vērtības daļa kopējā ražošanā bija attiecīgi 1,01 %, 0,28 % un 0,37 % [87].

Ražošanas tehnoloģiju energoefektivitāte

Yasin S. et al. apkopoja piecu tekstilizstrādājumu enerģijas patēriņu [156]. Četri izstrādājumi bija modes tekstilizstrādājumi, bet viens – mājas tekstilizstrādājums. Viens modes izstrādājums šajā analīzē netika iekļauts, jo tas neietilpst šī pētījuma tvērumā. Poliestera bikšu ražošanā tiek patērēts 20 % enerģijas, poliestera blūžu ražošanā – 98 %, bet džinsu ražošanā – 43 %. Aplūkotais mājsaimniecības tekstilizstrādājums bija kokvilnas aizkari, un to ražošanai tiek patērēti 70 % no kopējā aprites cikla enerģijas.

Lai iegūtu datus par tehniskajiem tekstilizstrādājumiem, tika izvēlēts ACN pētījums par vilnas un neilona paklājiem [157]. Tika apvienoti dati no trim procesiem, lai iegūtu enerģijas patēriņu ražošanas posmā – izejmateriālu ražošana, dzijas ražošana un paklāju flīžu ražošana. Neilona paklāju enerģijas patēriņš ir 18,67 MJ uz funkcionālo vienību, kas ir 73 % no kopējā enerģijas patēriņa. Vilnas paklāju ražošanā uz vienu funkcionālo vienību tiek patērēti 9,22 MJ, kas ir 45 % no kopējā enerģijas patēriņa. Turpmākajā analīzē izmantota vidējā vērtība.

Inovācijas spēja

Šā rādītāja ievaddati bija patenti, ko no 2015. līdz 2019. gadam tekstilizstrādājumu nozarēs iesniegušas nozares līdervalstis. Šīs valstis ir ES 27 dalībvalstis un Eiropas Brīvās tirdzniecības asociācijas valstis, Korejas Republika, Amerikas Savienotās Valstis, Ķīna, Japāna, Turcija, Apvienotā Karaliste, Indija un Vjetnama. Modes tekstilizstrādājumu, mājas tekstilizstrādājumu un tehnisko tekstilizstrādājumu nozarēs iesniegto patentu skaits bija attiecīgi 5001, 127 un 3440 [87].

Nodarbinātība un uzņēmumi

Šajā parametrā izmantoti dati bija par ES uzņēmumiem, jo nav datu par situāciju pasaulē. 2018. gadā nodarbināto skaits modes tekstilizstrādājumu, mājas tekstilizstrādājumu un tehnisko tekstilizstrādājumu nozarē bija attiecīgi 879 689, 191 916 un 150 920 darbinieku. Nodarbinātība mājas tekstilizstrādājumu un tehnisko tekstilizstrādājumu nozarē kopš 2015. gada ir palielinājusies, savukārt modes tekstilizstrādājumu nozarē tā ir samazinājusies par 2 %. Nodarbināto skaits modes tekstila, mājas tekstila un tehniskā tekstila uzņēmumos 2018. gadā bija attiecīgi 120 339, 26 182 un 14 688 [87].

3.1.2. Jauktā tekstila atkritumu pārstrādes analīzes piemērs

Identificētie tekstilmateriālu pārstrādes produkti

Tekstilmateriālu pārstrādes produktu identificēšanas rezultātā tika atlasīti 27 zinātniski raksti, kur analizēta tekstilmateriālu pārstrāde produktos. Lai varētu atlasīt rakstus atbilstoši izvirzītajiem kritērijiem, bija nepieciešama turpmāka kvalitatīvā analīze. **Metodes lietošana bioproduktu novērtēšanai**

FCM modelēšanas metode pētījumā izmantota, lai salīdzinātu dažādas ražošanas procesu metodes. Tā palīdzēs saprast, kura no metodēm vislabāk atbilst ilgtspējības kritērijiem, identificēt potenciālos šķēršļus, lai iegūtu uzticamus un objektīvus rezultātus, un noskaidrot, vai šāda veida integrētās analīzes izmantošana ir piemērota, lai salīdzinātu dažādas pētījumā aplūkotās ražošanas procesu alternatīvas. *FCM* modelēšana ir secīgs darbību kopums, kas nodrošinās, ka pētījuma mērķis tiek sasniegts caurspīdīgā un saprotamā veidā, lai analizētu sešpadsmit ražošanas procesus.

Lai salīdzinātu visus aprakstītos ražošanas procesus, ir jādefinē vissvarīgākie kritēriji. Šajā procesā tiek izmantoti vairāki kritēriji, padarot izvēles efektīvākas, racionālākas un skaidrākas. Analīzes mērķis ir strukturēt procesus, lai definētu mērķus, novērtētu iespējamos alternatīvas un salīdzinātu tās no dažādām perspektīvām. Izvērtējot prioritāros kritērijus, tika izvēlēti šādi kritēriji:

Produktu saraksts, kas iegūts no šiem rakstiem, ir redzams 3.2. tabulā. Astoņos rakstos tekstila atkritumu izcelsme bija industriāla, kas nav atbilstoši turpmākajai analīzei, jo šie tekstilmateriāli nav bijuši pakļauti lietotāja izmantojumam. Lielākā daļa rakstu koncentrējās uz noteikta veida tekstilmateriāliem vai to grupām; dažos gadījumos analizēti pat ļoti specifiski tekstilmateriāli, piemēram, zīds, džinss, liocels un āda.

Kā redzams 3.2. tabulā, tikai četri raksti atbilda abu kritēriju kopumam un attiecās uz jauktu pēcpatēriņa tekstilmateriālu pārstrādi. Atlasītajos pētījumos iegūtie produkti bija: (1) bioeļļa un tereftalskābe [8], (2) ar tekstilu pastiprināts kompozītmateriāls būvniecības vajadzībām [24], (3) tekstilšķiedras (kokvilna un neilons), spandeksa monomēri un bis(2-hidroksietil)tereftalāts [19], (4) uz micēlija bāzēts kompozītmateriāls siltumizolācijai [25].

Tekstila pārstrādē iegūstamie produkti

Tekstila veids	Industriālais tekstils	Pēcpatēriņa tekstils
Poliesters	Poliuretāna putas [26]	Tereftalskābe (TPA) [27], monomēri kā bis(2-hidroksietil)tereftalāts (BHET) un bis(2-hidroksietil)tereftalamīds [28], TPA un etilēnglikols [29]
Kokvilna	Siltumizolācija [30]	Kompozītmateriāli rūpnieciskiem mērķiem [31], glikozes šķīdums [32], [33], modes aksesuāri [34], vermikomposts mēslojumam [35]
Neilons	–	Smalki šķiedraina membrāna [36]
Džinss	Skaņu absorbējošs materiāls [37]	Ugunsizturīga kompozītplātne [38]
Zīds	–	Luminiscējoši oglekļa punkti [39]
Liocels	Smago metālu adsorbents [40]	–
Āda	Ādai līdzīgi dzijas pavedieni [41]	–
Kokvilna/poliesters	–	Celulozes šķiedras [42], celulozes un PET plēves [43], 3D drukas diegs [44], sēnīšu celulāze un poliesters [45]
Viskoze/poliesters un viskoze/poliamīds	–	Sintētiskās šķiedras un pienskābe [46]
Akrils un vilna	Siltumizolācija [47]	–
Kokvilna, kokvilna/poliesters un akrils	Bioogles kā auduma piedeva [48]	–
Jauktie tekstili	–	Bioeļļa un TPA [8], tekstila stiegrojuma kompozīti būvniecībai [24], BHET kristāli, spandeksa monomēri, kokvilna un neilons [19], uz micēlija bāzēts kompozītmateriāls siltumizolācijai [25]

Ievaddati alternatīvu salīdzinājumam

Turpmākajai *TOPSIS* analīzei tika izvērtēti produkti no četriem pētījumiem: (1) bioeļļa un tereftalskābe [8], (2) ar tekstila šķiedrām pastiprināts kompozītmateriāls būvniecībai [24], (3) tekstila šķiedras (kokvilna un neilons), spandeksa monomēri un bis(2-hidroksietil)tereftalāts [19] un (4) uz micēlija bāzēts kompozītmateriāls siltumizolācijai [25]. Tieši šie pētījumi atlasīti pētījumi, jo tajos aplūkota jau lietotu, sajauktu tekstila atkritumu pārstrāde.

A. Matayeva et al. 2022. gadā publicēja pētījumu par sajaukta tekstila pārstrādi, izmantojot hidrotermālo sašķidrināšanu [8]. Sajauktais tekstila atkritums tika simulēts, izmantojot pasaulē izplatītās šķiedru proporcijas un apģērbus no dažādiem materiāliem. Apstrāde notika

laboratorijas mērogā bez iepriekšējas apstrādes (piemēram, šķirošana, krāsvielu izņemšana utt.). Rezultāti parādīja, ka šī metode var nodrošināt 3–9 masas % bioeļļas un 38–54 masas % *TPA*. <u>Pēdējo</u> var tālāk izmantot plastmasas, iepakojuma, tekstila, sveķu, kompozītmateriālu, krāsu u. c. ražošanā [49]. Bioeļļas sastāvs šajā pētījumā ierobežo iespējas uzlabot to, lai izmantotu kā degvielu, bet to varētu izmantot kā ķīmisko izejvielu [8].

Otra tekstila pārstrādes alternatīva ir ar tekstila šķiedrām pastiprināts kompozītmateriāls (*TRC*), kas paredzēts būvniecības vajadzībām [24]. Prototipa plātnes tika izgatavotas laboratorijas mērogā, mehāniski ekstrudējot sajauktus tekstila atkritumus un izmantojot izotermisko karstspiedi tērauda formā. Kā sekundārā pildviela tika pievienotas mēbeļu industrijas kokskaidas. Lai uzlabotu apstrādes procesu un galaprodukta īpašības, izmantoti maleīnskābes anhidrīda modificēts polipropilēns un polipropilēna tekstila vilnas audums kā termoplastiska matricas fāze. Iegūtā materiāla īpašības ir pielīdzināmas kokskaidu plātnēm. Tās var izmantot nesošās konstrukcijās, grīdu un sienu sistēmās, iekšējā apdarē, piemēram, griestu vai akustisko paneļu veidā [24].

Trešais pētījums apskata slēgtā cikla pārstrādes iespējas, iegūstot BHET kristālus, spandeksa monomērus, kokvilnu un neilonu no jauktu tekstila atkritumu [19]. Izmantotā metode bija ķīmiskā pārveide, izmantojot mikroviļņu atbalstītu glikolīzi ar ZnO katalizatoru, kam sekoja šķīdināšana šķīdinātājā. Rezultātā poliesters pilnībā tika pārveidots BHET kristālos ar 93 % tīrību. Vērtīgākais iegūtais spandeksa monomērs bija 4,4′-metilēndianilīns, taču nepieciešama turpmāka optimizācija, lai palielinātu tā atlasamību pret citiem difenila savienojumiem. Skābe un krāsvielas palika uz iegūtās kokvilnas, kas apgrūtina turpmāku pārstrādi. Iegūtajam neilona materiālam bija samazināta molekulmasa, kas ierobežo tā lietojumu, kur nepieciešama augsta izturība un kušanas temperatūra. Kopumā metodes turpmāka attīstība varētu veicināt globālās tekstila pārstrādes slēgtā cikla īpatsvaru līdz 88 % [19].

Ceturtā analizētā alternatīva bija uz micēlija bāzēts kompozītmateriāls, kas paredzēts siltumizolācijai. Apskatītajā pētījumā [25] izstrādāts biokompozīts, audzējot *Pleurotus pulmonarius* sēnes uz agroindustriālajiem atkritumiem (zāles nogrieznēm, sausām lapām un cukurniedru atliekām) un sajauktiem, pēc patēriņa radušiem tekstila atkritumiem. Ievadmateriāls bija pārstrādāts tekstils, ko bija sagatavojis piegādātājs. Pētījums demonstrēja veiksmīgu tekstila izmantošanu sēņu audzēšanai, tādējādi radot ilgtspējīgu un izmaksu ziņā efektīvu būvmateriālu.

Pirms TOPSIS aprēķinu veikšanas ir jāapkopo katra produkta ievaddati. 10. tabulā apkopoti visi ievaddati, savukārt nākamajās apakšnodaļās aprakstīti datu avoti un pieņemtās pieņēmumu bāzes.

Daudzkritēriju lēmumu analīzes ievaddati (*MCDA*)

Kritēriji	Alternatīvas			
	Bioeļļa un TPA	Tekstila stiegrojuma kompozīts	BHET kristāli, spandeksa monomēri, kokvilna, neilons	Micēlija bāzes kompozīts
Ietekme uz vidi, reizes	0,99	2,63	6,83	4,59
Resursu efektivitāte, %	0	30	0	70
Ilgmūžība un pārstrādājamība, punkti	3,5	3	6	3
Produkta cena, reizes	1,07	0,05	1,65	18,33
Tirgus pieprasījums, miljardi EUR	44	7	27	65
Tehnoloģiskā gatavība, punkti	3	5	3	3
Izpētes līmenis, punkti	1	25	0	6
Tirgus konkurētspēja, punkti	1	2	1	1
Sociālie aspekti, punkti	4	6	1	9

Ietekme uz vidi

Lai novērtētu ietekmi uz vidi, tika analizēti dzīves cikla novērtējuma (*LCA*) pētījumi. Pirmajai alternatīvai vienlaicīgi tika ņemti vērā divi produkti. Līdz ar to katra kritērija izvērtējumā tika izmantota šo produktu vidējā vērtība. Bioeļļa tika salīdzināta ar pētījumu, kur bioeļļa tika iegūta no lauksaimniecības atkritumiem, izmantojot hidrotermālo apstrādi [50]. Šī produkta ietekme uz globālo sasilšanu (GSP) no izejvielu iegūšanas līdz vārtiem bija 2,05 kg CO_2 ekv./kg. Vērtējumā iekļauti arī oglekļa kvotas. Izmantotā *LCA* metode bija *ReCiPe*. Minētajā pētījumā jaunais produkts netika salīdzināts ar konvencionālo, tādēļ GSP tika iegūts no *Ecoinvent* datubāzes, izmantojot to pašu *LCA* metodi. Salīdzinājumam tika izvēlēta jēlnafta, jo pētījumā iegūtā bioeļļa nav tiešs fosilā kurināmā aizstājējs un tā ir jāapstrādā [8], [50]. Jēlnaftas GSP globālajā tirgū ir 0,65 kg CO_2 ekv./kg [51].

Nav pieejamu pētījumu, kuros *TPA* būtu iegūta ar hidrotermālo sašķidrināšanu, tāpēc salīdzinājumam izmantota biobāzēta *TPA*, kas iegūta, kā izejvielu termiski ķīmiskā procesā (ātrajā pirolīzē)izmantojot miskantes. Šī produkta GSP no izejvielu iegūšanas līdz robežvērtībai bija 1,04 kg CO_2 ekv./kg [52]. Tajā pašā pētījumā *TPA* tika salīdzināta ar konvencionālo *TPA*, kuras GSP tika novērtēts kā 1,72 kg CO_2 ekv/kg.

TRC (tekstilšķiedras kompozīts) tika salīdzināts ar LCA pētījumu, kurā aplūkoti kompozītmateriāli no dabīgām šķiedrām un pārstrādātiem tekstilizstrādājumiem [53]. Pētījumā nav norādīts, kādam nolūkam materiāli paredzēti. Atsauces materiāls bija kompozīts no linu un pārstrādātas poliestera tekstilšķiedras. Tā GSP no izejvielu ieguves līdz definētajai robežai bija 3.0 kg CO_2 ekv./kg. Tā kā pētījumā šie materiāli netika salīdzināti ar konvencionāliem produktiem, izmantots stiklšķiedras plastmasas GSP [54]. Izmantotā metode bija *ReCiPe Midpoint (E)*, un iegūtais GSP bija 7,9 kg CO_2 ekv./kg.

Trešās alternatīvas pētījums [28] atsaucas uz iepriekš veiktu *LCA* analīzi par šo pārstrādes procesu, kas tika izmantota kā references pētījums. Šajā references pētījumā [28] aprakstīja PET pudeļu pārstrādi BHET kristālos, izmantojot mikroviļņu palīdzību [55]. Iegūtais GSP bija 0,64 kg CO_2 ekv./kg. Tas tika salīdzināts ar konvencionālo BHET, kas iegūts no naftas, kura GSP bija 4,37 kg CO_2 ekv./kg. Šai alternatīvai tika ņemts vērā tikai viens produkts, kas iegūts ar vienu tehnoloģisko metodi. Tomēr analizētajā variantā izmantotā papildu apstrāde spandeksa monomēru, neilona un kokvilnas atdalīšanai netika ņemta vērā.

Micēlija bāzes materiāls tika salīdzināts ar LCA pētījumu, kurā analizēts micēlija izolācijas materiāls no zāģskaidām [56]. Iegūtais GSP bija 0,64 kg CO_2 ekv./kg. Lielākā daļa ietekmes (95 %) uz CO_2 aprēķina rezultātu bija saistīta ar elektroenerģiju, līdz ar to izejmateriāli būtiski neietekmēja rezultātu. Pētījums veikts Vācijā, kur elektroenerģijā ir augsts fosilo resursu īpatsvars, tāpēc ietekme citos reģionos varētu būt zemāka. Salīdzinājumam izmantots ekstrudētais polistirola izolācijas materiāls ar GSP 2,94 kg [56].

Resursu izmantošanas efektivitāte

Tikai divos gadījumos – *TRC* un micēlija bāzes kompozītos – tika konstatēta papildu izejmateriālu izmantošana no pārstrādātiem atlikumiem. *TRC* gadījumā mēbeļu rūpniecības koksnes šķiedras tika izmantota kā otrā pildviela, veidojot 30 % no materiāla svara [24]. Micēlija materiālam nepieciešams lignocelulozes substrāts, no kura sēne barojas. Kā izejvielu var izmantot dažādas augu izcelsmes vielas, piemēram, džutu, linu un salmus [57]. Gomeza u. c. pētījumā tika izmantoti lauksaimniecības atkritumi (nogrieztie zāles stiebri, sausās lapas un cukurniedru atliekas [25]), kas veidoja 70 % no substrāta masas.

Ilgmūžība un pārstrādājamība

Bioeļļu iespējams izmantot kā kurināmo un dažādu produktu, piemēram, pārtikas aromātu, aromātisko savienojumu, olefīnu, sveķu, līmju, augu aizsardzības līdzekļu un mēslojumu, ražošanā [58]. Lielākā daļa šo preču ir vienreizlietojamas un nav pārstrādājamas. *TPA* izmanto plastmasas, iepakojuma, tekstila, sveķu, kompozītmateriālu un krāsu ražošanā [49]. Tā kā *TPA* iespējams izmantot tekstilizstrādājumu ražošanā, šajā analīzē tas uzskatīts par potenciāli pārstrādājamu slēgtā ciklā. Tekstila vidējais dzīves cikls ir līdz sešiem gadiem [59].

Šķiedru kompozītu pārstrāde ir izaicinoša to izturības un ķīmiskās stabilitātes dēļ [60], [61], līdz ar to *TRC* šajā analīzē tika uzskatīts par nepārstrādājamu. Tā kā *TRC* paredzēts būvniecībai, tā kalpošanas laiks pārsniedz 10 gadus, jo ēku ilgmūžība tiek vērtēta robežās no 20 līdz pat vairāk nekā 100 gadiem [62].

Andini u. c. pētījumā iegūtās tekstila šķiedras (neilons un kokvilna), spandeksa monomēri un BHET kristāli ir pārstrādājami tekstilizstrādājumu ražošanā [19], tādēļ analīzē tika pieņemts, ka šiem produktiem iespējams nodrošināt slēgta cikla pārstrādi. Tā kā pārstrādes iespējas attiecas uz tekstilizstrādājumiem, tika pieņemts to dzīves cikls līdz 10 gadiem.

Micēlija bāzes materiāli tiek uzskatīti par bioloģiski noārdāmiem [63], tomēr analizētajā gadījumā daļa substrāta sastāv no jaukta tekstila, kas satur sintētiskas šķiedras. Tādējādi šāds materiāls, visticamāk, nav pilnībā noārdāms, jo sintētiskais tekstils nav bioloģiski noārdāms [64].

Produkta cena

TPA cena tika iegūta no sociālekonomiskā pētījuma par PET enzimatiskās pārstrādes procesu, lai iegūtu *TPA* [65]. Pētījumā tika noteikta minimālā pārdošanas cena – 1,93 USD/kg, kas tika salīdzināta ar jauna *TPA* 2021. gada tirgus cenu, kas bija aptuveni 1 USD/kg [65]. Attiecībā uz bioeļļu tika izmantots piemērs no pētījuma, kurā bioeļļa iegūta no pārtikas atkritumiem, izmantojot hidrotermisko oksidāciju [66]. Tajā tika noteikta minimālā pārdošanas cena 104 USD/tonnā, bet tirgus cena tika noteikta 168 USD/tonnā [66].

TRC cenas pētījumos netika konstatētas, tāpēc tika izpētītas šķiedru kompozītmateriālu cenas. Vienā pētījumā apkopotas hibrīdo dabīgo un sintētisko šķiedru kompozītu cenas dažādiem lietojumiem. Pētījumā apkopotas 144 produktu cenas [67], un aprēķinos izmantota vidējā vērtība – 12,15 USD/kg. Tāpat kā vides ietekmes kritērijā, arī šeit tika salīdzināts ar stikla šķiedras kompozītmateriālu. Tā ekonomiskie rādītāji netika atrasti zinātniskajā literatūrā, tāpēc izmantoti tiešsaistes veikali. Tajos stikla šķiedras kompozītmateriāla cena bija robežās no 0,61 USD/kg līdz 0,71 USD/kg [68]. Aprēķinos tika izmantota vidējā vērtība.

Attiecībā uz trešo alternatīvu netika meklēta salīdzināma cena, jo process rada vairākus produktus un ir ļoti inovatīvs. Turklāt pats pētījums ietvēra sociālekonomisko novērtējumu, kas precīzāk atspoguļo ekonomisko sniegumu [19], tādēļ šai alternatīvai tika salīdzināts investīciju apjoms. Sociālekonomiskajā novērtējumā par jaukta sastāva tekstila pārstrādi tika pieņemts tekstila ievades daudzums – 500 kg/h [19]. Pieņemot projekta ekonomisko dzīves ciklu 10 gadu garumā tika aprēķinātas kopējās ekspluatācijas izmaksas – 92,3 miljoni USD gadā, un kapitālizmaksas – 6,5 miljoni USD gadā. Šie dati tika salīdzināti ar konvencionālās BHET ražošanas izmaksām – ekspluatācijas izmaksas 173,51 miljons USD gadā, kapitālizmaksas – 38,69 miljoni USD gadā [55]. Tā kā vienā pētījumā norādītas gada kapitālizmaksas, bet otrā – kopējās izmaksas, veikti aprēķini, lai iegūtu salīdzināmas kopējās izmaksas. Tās aprēķinātas, izmantojot kapitāla atgūšanas likmes formulu [69], ņemot vērā projekta ilgumu un procentu likmi [19].

Lai noteiktu aptuveno cenu ceturtajai alternatīvai, izmantots pārskata raksts par micēlija materiāliem [70]. Tajā norādītas micēlija bāzes materiālu vidējās cenas un salīdzinājums ar polimēru materiāliem. Micēlija materiālu cenas svārstās no 0,07 USD/kg līdz 0,17 USD/kg, savukārt polimēru materiālu cenas – no 2,1 USD/kg līdz 2,3 USD/kg. Salīdzināšanai izmantotas vidējās vērtības.

Tirgus pieprasījums

Lai nodrošinātu salīdzināmību, visi tirgus novērtējumi tika veikti par vienu gadu – 2023. gadu. Attīrītās tereftalskābes (*TPA*) pasaules tirgus tika novērtēts 78 miljardu USD apmērā [71]. Bioeļļas tirgus 2023. gadā tika lēsts 10,7 miljardu USD apmērā [72]. Būvniecības kompozītmateriālu tirgus tika novērtēts 6,88 miljardu USD apjomā [73]. Siltumizolācijas materiālu pasaules tirgus apjoms tika novērtēts 65,11 miljardu USD apmērā [74]. Trešās alternatīvas BHET kristālu tirgus novērtējumi netika atrasti, tādēļ tika aplūkots no BHET kristāliem iegūts PET [19]. Papildus analizēts pārstrādātās kokvilnas tirgus, ņemot vērā, ka PET un kokvilna veido lielāko daļu no gatavajiem produktiem. PET globālais tirgus tika lēsts 48,43 miljardu USD apmērā [75], bet pārstrādātās kokvilnas tirgus – 5,2 miljardu USD apmērā [76].

Tehnoloģiju gatavības līmenis

Tikai vienai alternatīvai – micēlija materiāliem – pārskatīto pētījumu autori bija veikuši *TRL* novērtējumu [25]. Šī tehnoloģija tika novērtēta *TRL 3* līmenī. Pirmie divi *TRL* līmeņi aptver tehnoloģiskā koncepta izstrādi, savukārt trešajā līmenī tiek veikta koncepta eksperimentāla vai analītiska testēšana [22]. Micēlija materiāla gadījumā tehnoloģija tiek attīstīta laboratorijas apstākļos, testējot tās īpašības.

Attiecībā uz pārējām alternatīvām *TRL* noteikts, balstoties uz katrā pētījumā sniegto informāciju. Pētījumā par pirmo alternatīvu tika norādīts, ka pirmo reizi pierādīts, ka hidrotermiskā sašķidrināšana var apstrādāt jaukta sastāva tekstila atkritumus [8], tāpēc tika piešķirts *TRL 3*. *TRC* pētījumā uzsvērts, ka materiāla vienkāršais ražošanas process liecina par tā potenciālu pāriet no laboratorijas uz pilotražošanu [24], tāpēc šai alternatīvai tika piešķirts *TRL 5*, jo *TRL 6* līmenī notiek prototipa demonstrācija atbilstošā vidē [22]. Trešajai alternatīvai tika piešķirts *TRL 3*, jo laboratorijā tiek testēts jauns koncepts un vēl nepieciešami procesa uzlabojumi [19].

Pētījumu apjoms

Par pirmo alternatīvu ir veikts tikai viens cits pētījums, kurā analizēts pārstrādes process un iegūtie produkti. Otrais pētījums, kas ir salīdzinoši nesens, izmanto to pašu metodi, lai pārstrādātu tekstilšķiedras bioeļļā un *TPA* [77]. Abi pētījumi veikti viena un tā paša autora vadībā. Galvenā atšķirība ir izejmateriālos – izmantoti dažādi kokvilnas un poliestera sajaukumi.

TRC joma ir salīdzinoši labi izpētīta. Meklējot informāciju, tika atrasti vairāk nekā 100 rezultāti, taču pārskatīti tika pirmie 25. Lai šī kritērija ietvaros ierobežotu pārāk plašo diapazonu un mazinātu pārskatāmo rakstu skaitu, tika noteikts, ka maksimālais punktu skaits būs 25. Pētījumos aplūkoti dažādi kompozītmateriāli, galvenokārt no industriālajiem tekstilatkritumiem [78], [79], [80], izmantojot vienu [81], [82] vai vairākus [83], [84] tekstila veidus, un visi bija paredzēti būvniecības nozarei.

Meklējot pētījumus, kas līdzīgi trešajai alternatīvai, tika atrasti tikai divi rezultāti, no kuriem viens bija šajā darbā analizētais raksts. Otrais atrastais pētījums bija vērsts uz tekstila apstrādi – uz PET tekstila izgatavošanu ar noturīgu hidrofilu virsmu, izmantojot mikroviļņu asistētu glikolīzi [85]. Tā kā šeit tekstils tika apstrādāts, nevis pārstrādāts, šis pētījums netika uzskatīts par atbilstošu. Līdz ar to nav citu līdzīgu pētījumu par trešo alternatīvu.

Meklējot pētījumus par micēliju un tekstilu, tika atrastas 35 publikācijas, no kurām sešas bija precīzi atbilda pētamajam objektam. Daudzos pētījumos tekstils minēts tādēļ, ka micēliju var izmantot tekstilam līdzīgu materiālu, piemēram, mākslīgās ādas izgatavošanā. Tika atrasti divi raksti, kuros tekstils izmantots kā substrāts sēņu audzēšanai. *Ruiz et al.* izstrādāja uz micēlija bāzētu kompozītmateriālu būvniecības nozarei, izmantojot džinsa audumu un lauksaimniecības atkritumus [86]. Otrajā pētījumā tika izstrādāti biokompozīti kā alternatīva plastmasas iepakojuma produktiem, izmantojot kokvilnu un poliestera šķiedras kā izejvielu [87]. Šajā pētījumā netika izmantoti papildu biomases substrāti. Pārējos četrus pētījumus veica *Jiang et al.*, un tie bija vērsti uz vienu produkta veidu: biokompozīta slāņveida materiālu [88], [89], [90], [91]. Iegūtais materiāls ir daudzslāņu kompozīts, kurā visi materiāli ir dabiskas

izcelsmes. Tas ietver dabīgas tekstilšķiedras kā virsmu, micēlija savienotus lauksaimniecības atkritumus kā serdi un bioloģiskos sveķus kā matricu [90].

Tirgus konkurētspēja

TPA un bioeļļas gadījumā par galveno īpašību tika izvēlēts iegūtais produkta iznākums. Kā jau iepriekš minēts, pētījumā sasniegti šādi rādītāji – 3–9 % bioeļļas un 38–54 % *TPA* [8]. Visizplatītākā *TPA* ražošanas tehnoloģija ir *Mid-Century* jeb *AMOCO* process, kurā parasti iegūst 95 % *TPA* [49]. Tipiskais bioeļļas iznākums, izmantojot hidrotermālo sašķidrināšanu, ir no 24 % līdz 64 % [92].

TRC gadījumā pētījumā iegūtie rādītāji tika pārbaudīti un salīdzināti ar standarta koksnes skaidu plākšņu parametriem, pamatojoties uz ISO 16893:2016 [24]. Līdz ar to nebija jāmeklē papildu salīdzinājuma materiāli. Kopumā materiāla īpašības bija optimālas, un mitruma izturības rādītāji pārsniedza nepieciešamo – tie bija ievērojami zemāki nekā standarta noteiktie, kas norāda uz augstu izturību pret mitrumu [24].

Trešās alternatīvas gadījumā tikai viens no produktiem – BHET kristāli ar 93 % tīrību un iespēju panākt $\geq$ 99 % tīrību – bija pielīdzināms tradicionālajam produktam [19]. Citiem produktiem nepieciešami turpmāki pētījumi un optimizācija. Piemēram, lai uzlabotu 4,4′-metilēndianilīna selektivitāti, ir nepieciešama spandeksa monomēru apstrādes procesa pilnveide. Kokvilnas šķiedrās joprojām ir atlikušās reaktīvās krāsvielas un to polimerizācijas pakāpe ir samazināta, tāpēc nepieciešama padziļināta izpēte, lai iegūtu augstāku kvalitāti. Arī neilona vidējais molekulārais svars ir samazināts. Līdz ar to jānosaka optimālie apstrādes apstākļi, kas nodrošinātu krāsu atdalīšanu un molekulārās masas saglabāšanu [19].

Micēlija kompozītmateriālam tika testētas četras īpašības: spiedes izturība, stiepes izturība, elastības modulis un siltumvadītspēja [25]. Tā kā šis materiāls paredzēts siltumizolācijai, tieši siltumvadītspēja tika izvēlēta salīdzināšanai. Tika iegūti šādi rādītāji: 1,04 $\pm$ 0,17 W/mK (no zāles un sausajām lapām) un 0,85 $\pm$ 0,02 W/mK (cukurniedru atlikumiem) [25]. Šie rezultāti salīdzināti ar citu micēlija materiālu datiem un secināts, ka tekstila pievienošana siltumvadītspēju uzlabo. Tomēr rādītāji joprojām ievērojami pārsniedz tirgū pieejamos risinājumus, piemēram, putupolistirola siltumvadītspēja ir 0,030–0,045 W/mK [93].

Sociālie aspekti

Bioeļļas un *TPA* ražošanas procesā identificētie riski un ietekme uz veselību ir novērtēti kā vidēji – ikdienas darba veicējiem tiešs apdraudējums netiek identificēts. Tomēr hidrotermālās sašķidrināšanas process notiek paaugstinātā temperatūrā un spiedienā, kas rada apdegumu un eksplozijas risku [94]. Arī šī iemesla dēļ darbinieku kvalifikācijas līmenis novērtēts kā vidējs – nepieciešama inženiertehniska izglītība.

Kompozītmateriālu ražošana kopumā saistīta ar toksisku vielu izraisītiem riskiem, piemēram, šķidrumu, tvaiku vai šķiedru daļiņu ieelpošanu [95]. Šajā pētījumā iespējami galvenie riski bija tekstila un koksnes putekļi [24]. Ir pierādīts, ka koksnes putekļi ir cilvēka kancerogēns [96]. Darba iespējas šajā ražošanā tiek uzskatītas par vairāku prasmju līmeņu darbavietām – process ir salīdzinoši vienkāršs, bet nepieciešami inženieri un citi speciālisti [24].

Trešās alternatīvas ķīmiskās pārstrādes process tika novērtēts kā visbīstamākais no visiem analizētajiem. Tas saistīts ar izmantoto un nākotnē potenciāli izmantojamo ķīmisko vielu ietekmi, piemēram, etilēnglikolu, kas ir klasificēts kā toksisks cilvēkiem saskaņā ar *REACH* [97]. Šādi pārstrādes procesi prasa augsti kvalificētu darbaspēku, kas spēj izstrādāt un uzturēt jaunās tehnoloģijas un procesus [98].

Savukārt micēlija materiālu ražošana sastāv no salīdzinoši vienkāršiem soļiem [25]. Sākotnēji tiek sagatavots substrāts, nodrošināts atbilstošs mitruma un pH līmenis, tad substrāts tiek pasterizēts. Pēc tam tiek pievienots sēņu micēlijs un sākas audzēšana. Pēc audzēšanas tiek veikta dehidrācija, lai deaktivizētu micēliju. Ražošanas posmā nav būtisku apdraudējumu – netiek izmantota nedz augsta temperatūra, nedz bīstamas ķīmiskās vielas. Izmantotās sēnes cilvēka veselībai nav kaitīgas [99]. Vienkāršais process ļauj nodrošināt darba iespējas dažādu prasmju līmeņu darbiniekiem. Tā kā ražošanā ir iesaistīta arī micēlija audzēšana, ir nepieciešami arī augsti kvalificēti speciālisti.

TOPSIS metode

Pēc ievaddatu noteikšanas veikti aprēķini, izmantojot *TOPSIS* metodi. Rezultāti redzami 3.1. attēlā. Atbilstoši daudzkritēriju izvērtējumam visaugstāko rezultātu (0,64) sasniedza micēlija bāzes materiāls, tāpēc tas novērtēts kā vispiemērotākais risinājums. Šī alternatīva atbilda ideālajām vērtībām četros kritērijos un vienlaikus sasniedza trīs antiideālās vērtības.

Pārējām alternatīvām antiideālo vērtību bija vairāk: bioeļļa un *TPA* – četras, *TRC* – trīs, bet BHET kristāli, spandeksa monomēri un kokvilnas/neilona maisījums – piecas. Bioeļļa un TPA nesaņēma nevienu ideālo vērtību un kopvērtējumā ieguva viszemāko rezultātu.
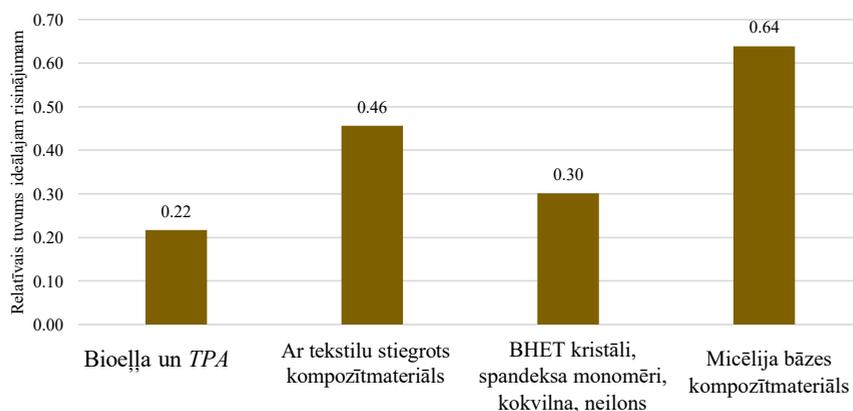
3.1. attēls. *TOPSIS* analīzes rezultātā iegūtais alternatīvu vērtējums.

Katras alternatīvas normalizētie un svērtie kritēriju rādītāji ir redzami 3.2. attēlā. Kā redzams, vislielākais attīstības potenciāls ir materiālam, kura pamatā ir micēlijs, jo tas ir salīdzinoši labi izpētīts un tam ir vienkāršs ražošanas process. Tā ekonomiskā dzīvotspēja un tirgus potenciāls ir ļoti augsts. Materiālam ir arī nozīmīgas vides priekšrocības, un to iespējams ražot no plaša spektra atkritumiem un blakusproduktiem. Šī produkta vājā puse ir tā īpašības salīdzinājumā ar tirgū pieejamajiem produktiem. Tomēr šajā pētījumā tika salīdzināts tikai

siltumvadītspējas rādītājs. Katrā ziņā nepieciešami turpmāki pētījumi, lai optimizētu produkta īpašības un izpētītu citas lietojuma iespējas.
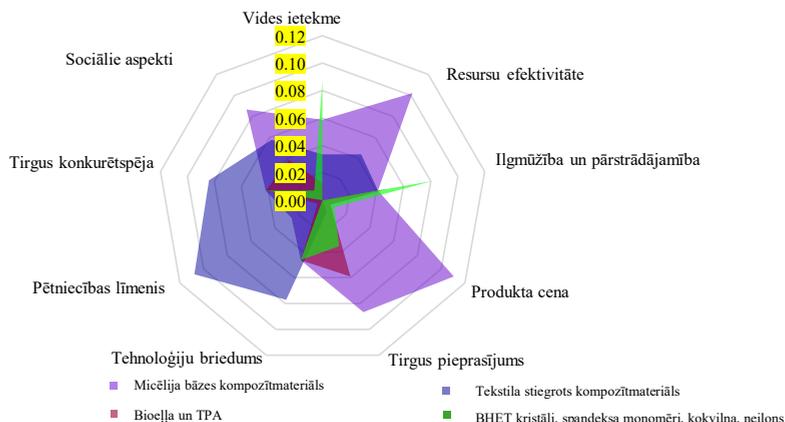

3.2. att. Katrai alternatīvas visu kritēriju standartizētie svērtie punkti.

Jutīguma analīze

Jutīguma analīze veikta, lai novērtētu, kā analīzes rezultāti mainās atkarībā no kritēriju svaru izmaiņām. Analizēti visi iekļautie kritēriji. Lielākajā daļā gadījumu – astoņos no deviņiem kritērijiem – micēlija bāzes materiāls saglabāja savu pozīciju kā labākā alternatīva. Tas norāda, ka arī svaru izmaiņu gadījumā daudzkritēriju analīzē šis risinājums saglabā stabilas priekšrocības.

Vienīgais kritērijs, kurā micēlija bāzes materiāls zaudēja pirmo vietu, bija "Pētījumu līmenis" (sk. 3.3. attēlu). Ja šī kritērija svars tiktu palielināts vismaz 1,5 reizes, par labāko alternatīvu kļūtu *TRC* materiāls, jo *TRC* ir otra labākā alternatīva un salīdzinoši daudz vairāk pētīta nekā pārējās.
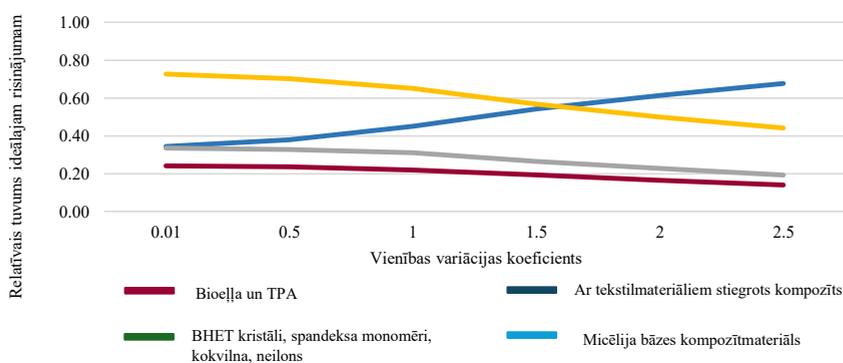
3.3. att. Kritērija "Pētījumu līmenis" jutīguma analīzes rezultāti.

3.1.3. CO₂ uzglabāšanas mežizstrādes atlikumos analīzes piemērs [90]

Uzkrātā biogēnā CO_2 daudzums jaunā šķiedru plātņu izolācijas materiālā astoņiem dažādiem uzskaites standartiem ir parādīts 3.4. tabulā. Uzglabātais daudzums ir aprēķināts vienam kubikmetram jaunam šķiedru plātņu izolācijas materiālam.

3.4. tabula.

Uzkrātais biogēnais CO_2 atkarībā no uzskaites standarta

Tehniskais standarts	Uzglabātais CO_2, kg/m³	Avots
EN-15804 (2012)	359	[96]
ISO/DIS-21930 (2015)	251	[158]
EN-15804 (2012) +A1:2013	359	[96]
CEN/TR-16970 (2016)	359	[96]
EN-16485 (2014)	359	[96]
ISO/TS-14067 (2013)	90	[159]
PEF v2.2 (2016)	90	[159]
PAS-2050 (2011)	291	[160]

Standartiem EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) un EN-16485 (2014) aprēķinātais uzkrātā CO_2 daudzums ir vienāds, jo tie visi ir balstīti uz vienu un to pašu standartu EN-15804 (2012) un pieņem, ka daudzums tiek aprēķināts pēc ISO/TS-14067 (2013) un PEF v2.2 (2016). Standartu pamatā ir iepriekšējo ISO-14040/44 standartu ACN, un tie neatšķīrās uzkrātā CO_2 daudzuma aprēķināšanā.

EN-15804 standartā balstītie standartos ir norādīts lielākais uzkrātā CO_2 daudzums vienā kubikmetrā produkta – 359 kg CO_2/m³, savukārt vismazākais uzkrātā CO_2 daudzums ir standartos, kas balstīti uz iepriekšējo ISO-14040/44 ACN standartu – 90 kg CO_2/m³. Ņemot vērā visus standartus, ja netiek izvēlēta viena oglekļa uzskaites metode, par galarezultātu var pieņemt vidējo vērtību – 270 kg CO_2/m³ uzkrātā CO_2.

Trīs dažādu enerģijas ražošanas scenāriju daudzkritēriju analīzei aprēķinātās kritēriju vērtības un svarīgums ir parādīti 3.5. tabulā.

Kritēriju vērtības un svarīgums

	Koksnes biomasas koģenerācija	Dabasgāzes koģenerācija	Koksnes biomasa *CP* + PV paneļi	Kritēriju svars
Kurināmā enerģētiskais saturs, GJ/m³	1,56	2,26	1,10	0,079
Kapitāla izmaksas, EUR/m³	12,68	38,01	8,45	0,210
Degvielas izmaksas, EUR/m³	55,17	37,75	47,80	0,288
O&M izmaksas, EUR/m³	1,10	0,94	0,89	0,152
Pirktā/pārdotā elektroenerģija, EUR/m³	3,84	−9,45	19,77	0,110
NO$_X$ emisijas, g/m³	3,14	4,95	2,36	0,028
CO emisijas, g/m³	0,86	5,78	0,64	0,016
GOS emisijas, g/m³	0	4,95	0	0,020
PM emisijas, g/m³	4,7	0	3,5	0,040
CO$_2$ emisijas, kg/m³	0	90	0	0,057

Trīs dažādu enerģijas ražošanas scenāriju daudzkritēriju analīzes rezultāti ir parādīti 3.4. attēlā.
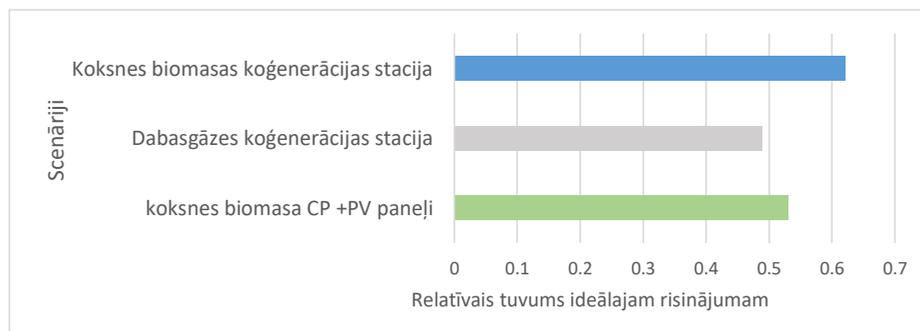
3.4. att. Daudzkritēriju lēmumpieņamšanas analīzes rezultāti.

Daudzkritēriju analīzes rezultāti liecina, ka labākais enerģijas ražošanas scenārijs ir koksnes biomasas koģenerācijas stacija (0,622). Otrajā vietā ir koksnes biomasas sadedzināšanas iekārtas un saules fotoelementu paneļu scenārijs (0,531), kas tikai nedaudz apsteidz dabasgāzes koģenerācijas stacijas scenāriju (0,490), lai gan pašlaik daudzkritēriju analīze liecina, ka dabasgāzes fosilo resursu izmantošanas scenārijs ir salīdzinoši tuvu vērtējumam salīdzinājumā ar dabasgāzes izmantošanas scenāriju.

Dabasgāzes koģenerācijas stacijas scenārija novērtējums nākotnē varētu samazināties, jo pasaulē arvien vairāk tiek izmantoti atjaunojamie resursi. Tomēr dabasgāzes koģenerācijas

staciju scenārijs joprojām ir jāpārskata un jāņem vērā, lai varētu skaidri parādīt, ka ir labākas alternatīvas, proti, koksnes biomasas koģenerācijas un sadedzināšanas iekārtas. Lai to vēl vairāk uzsvērtu, būtu jāveic detalizētāki pētījumi, kuros jāņem vērā gan kvantitatīvie, gan kvalitatīvie dati, tostarp nozares ekspertu un uzņēmumu dati un viedokļi. Turpmākajos pētījumos būtu jāizskata arī sociālie un politiskie aspekti. Tas savukārt varētu būtiski ietekmēt dažādu enerģijas ražošanas scenāriju novērtējumus, iespējams, palielinot atjaunojamo enerģijas avotu scenāriju novērtējumu, lai tie tiktu atzīti par nepārprotamiem favorītiem salīdzinājumā ar fosilo resursu izmantošanu.

3.2. Aprites cikla novērtējums (ACN)

3.2.1. Pārstrādāti šķērsām līmēti kokmateriāli kā zemas ietekmes uz vidi neapstrādāta materiāla alternatīva: Latvijas gadījuma izpēte

Pārstrādātā *CLT* starpposma un beigu posma ietekme

Attiecībā uz pārstrādāto *CLT* vislielākā ietekme lielākajā daļā kategoriju ir abiem līmēšanas procesiem. Abos procesos tiek izmantotas naftas produktu pārstrādes līmes. Trešā lielākā ietekme ir koksnes šķelšanai, kas uzrāda vislielāko ietekmi uz saldūdens eitrofikāciju un jūras eitrofikāciju. Šajā procesā tiek patērēts visvairāk enerģijas uz vienu funkcionālo vienību (FV). Ietekme zemes izmantošanas kategorijā liecina, ka gandrīz visa pārstrādātā *CLT* ietekme ir saistīta ar otro līmēšanu un presēšanu (sk. 3.5. att.). Tas ir saistīts ar neapstrādāta materiāla izmantošanu, jo šajā gadījumā ārējā slāņa ražošanai tika iegūtas primārās izejvielas, nodrošinot identisku vizuālo kvalitāti kā jaunam *CLT*.
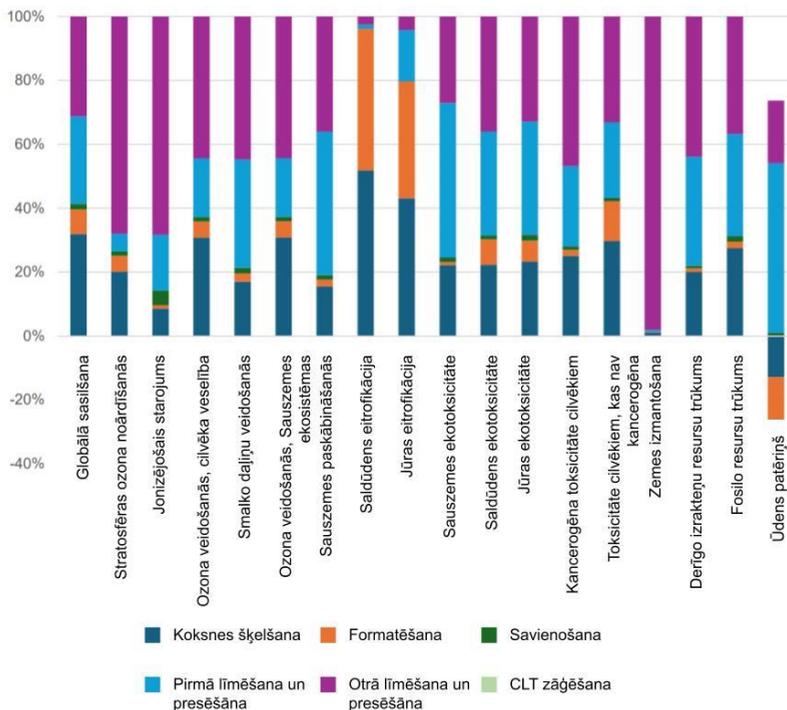
3.5. att. Iespējamā ietekme uz 1 m³ šķērsām līmētas koksnes potenciāla rezultātu viduspunktu.

Attiecībā uz galīgo ietekmi (sk. 3.6. att.), izmantojot *ReCiPe* metodoloģiju, tika novērtētas trīs kategorijas: cilvēku veselība, ekosistēma un resursi. Analīze parādīja, ka cilvēka veselībai kategorijā bija vislielākā ietekme ar vienu punktu, kas deva 3,68 Pt. Arī šajā gadījumā līmēšanas procesi veidoja vairāk nekā pusi no ietekmes, bet trešajā vietā bija koksnes šķelšana. Ekosistēmas ietekmes kategorijā lielāko ietekmi uzrādīja otrā līmēšana ar *PUR* līmi, kas veidoja pusi no kopējās ietekmes. Resursu kategorijā ietekme bija vismazākā, jo šajā procesā netiek izmantoti nekādi reti elementi un lielākā daļa funkcionālo vienību (FV) ir izgatavota no atjaunojamiem materiāliem.
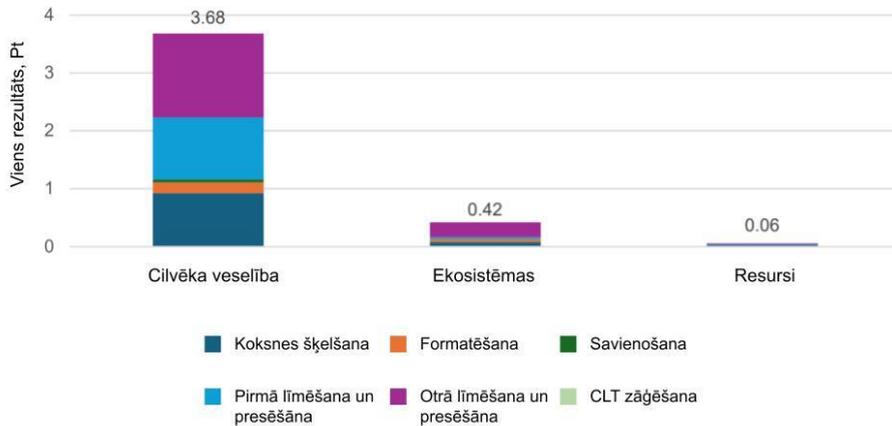
3.6. attēls. Pārstrādātas šķērsām līmētas koksnes 1 m^3 ietekme uz galīgo vienoto rādītāju.

Pārstrādātā *CLT* un *CLT* viduspunkta un beigu posma ietekmes salīdzinājums

Lai patiesi novērtētu ieguvumus no otrreizējās pārstrādes tehnoloģijas izmantošanas, pārstrādātais *CLT* tika salīdzināts ar *CLT*, izmantojot viduspunkta un beigu posma rādītājus, kas parāda katra produkta ietekmi, ļaujot veikt salīdzinājumu. Salīdzinot starpposma rādītājus (sk. 3.7. att.), gandrīz visās ietekmes kategorijās pārstrādātā *CLT* FV ietekme ir mazāka. Vienīgais izņēmums, kur pārstrādātais *CLT* uzrāda lielāku negatīvo ietekmi, ir eitrofikācijas kategorijas, kas saldūdens eitrofikācijai rada 0,48 kg fosfora ekvivalentu un 0,36 kg slāpekļa ekvivalentu. Šī ietekme ir saistīta ar nepareizu biomasas atlieku apglabāšanu [36], tāpēc dažas no šajā pētījumā minētajām ietekmēm varētu būt saistītas ar zāģskaidu apglabāšanu. Ievērojamākie uzlabojumi ir globālās sasilšanas, zemes izmantošanas un sauszemes ekotoksicitātes ietekmes kategorijās.

Pārstrādāta šķērsām līmētas koksnes (pārstrādātā *CLT*) un šķērsām līmētu kokmateriālu 1 m^3 garuma potenciālā ietekme uz vidusposmu

Ietekmes kategorija	Vienība	ReCLT	CLT
Globālā sasilšana	kg CO_2 ekv.	82,76	151,24
Stratosfēras ozona noārdīšanās	kg CFC11 ekv.	0,00006	0,00017
Jonizējošais starojums	kBq Co-60 ekv.	3,96	16,73
Ozona veidošanās, cilvēka veselība	kg NO_X ekv.	0,23	0,87
Smalko daļiņu veidošanās	kg PM2,5 ekv.	0,11	0,38
Ozona veidošanās, sauszemes ekosistēmas	kg NO ekv.,	0,24	0,92
Sauszemes paskābināšanās	kg SO_2 ekv.	0,26	0,56
Saldūdens eitrofikācija	kg P eq	0,54	0,06
Jūras eitrofikācija	kg N ekv.	0,049	0,013
Sauszemes ekotoksicitāte	kg 1,4-DCB	2302,88	4243,63
Saldūdens ekotoksicitāte	kg 1,4-DCB	3,80	6,11
Jūras ekotoksicitāte	kg 1,4-DCB	6,82	12,93
Kancerogēna toksicitāte cilvēkiem	kg 1,4-DCB	15,35	36,44
Toksicitāte cilvēkiem, kas nav kancerogēna	kg 1,4-DCB	94,98	153,25
Zemes izmantošana	m^2 kultūraugu ekvivalents	94,08	861,79
Derīgo izrakteņu resursu trūkums	kg Cu ekv.	0,26	0,48
Fosilo resursu trūkums	kg naftas ekv.	23,33	46,78
Ūdens patēriņš	m^3	0,63	1,81

Pārstrādātā *CLT* uzrāda ievērojamāku negatīvu ietekmi uz saldūdens un jūras eitrofikācijas kategorijām, un tas var būt saistīts ar līmēšanas procesā izvēlēto amonija sulfāta cietinātāju. Relatīvais ietekmes salīdzinājums viduspunktā ir parādīts 22. attēlā, parādot pārstrādātā *CLT* proporcionālos ieguvumus, jo īpaši zemes izmantošanas kategorijā.
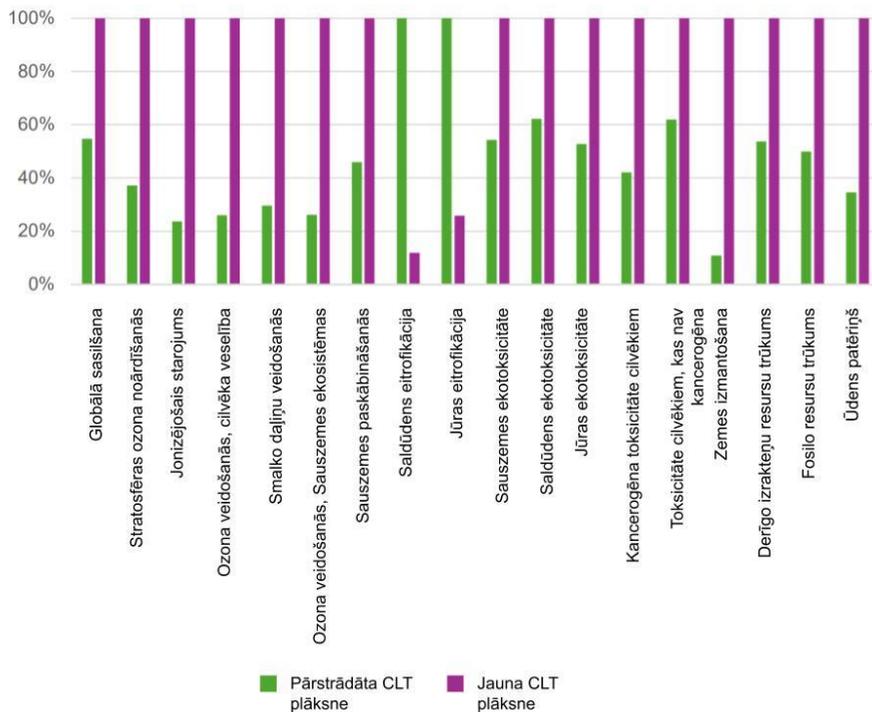
3.7. attēls. Iespējamā ietekme uz 1 m³ vidējo posmu pārstrādātas šķērsām līmētas koksnes (pārstrādātā *CLT*) un jaunas šķērsām līmētas koksnes (*CLT*).

Apkopotais ietekmes salīdzinājums ir parādīts pēc gala posma, izmantojot vienoto rezultātu (sk. 3.8. att.), kas atkal parāda, ka pārstrādātā *CLT* akumulē mazāku negatīvo ietekmi, salīdzinot ar jaunu *CLT*, ar gandrīz 60 % samazinātu kaitējumu cilvēku veselībai un vairāk nekā 80 % samazinātu kaitējumu ekosistēmai, bet vismazākais samazinājums ir 50 % resursu kategorijā.
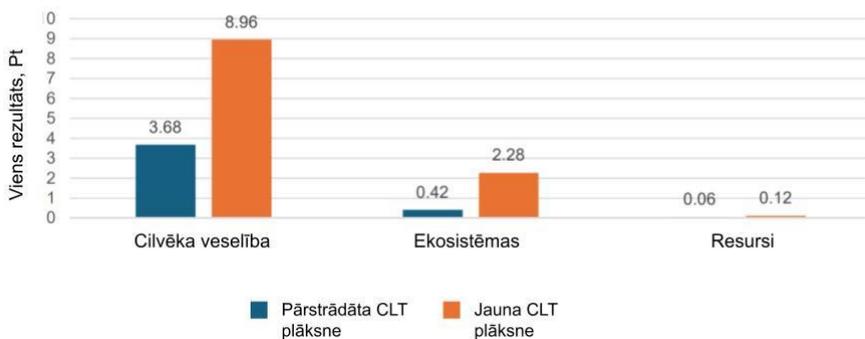
3.8. attēls. Pārstrādāta šķērsām līmētas koksnes (pārstrādātā *CLT*) un jaunas šķērsām līmētas koksne (*CLT*) ietekme uz gala punktu ar vienu rezultātu.

3.2.2. Jaukto tekstilizstrādājumu pilnīgas dzīves cikla analīzes trūkums

Otrs ACN piemērs kalpoja, lai aprakstītu ierobežojumus un pieņēmumus, kas ir izmantoti kokvilnas un poliestera maisījumu vides novērtējumos. Šajā piemēra tika izmantotas divas metodes bibliometriskā metode ar literatūras analīzi, gan aprites cikla novērtējums.

Lai izmantotu aprites cikla novērtējumu kā bāzes modeli, izmantots ACN pētījums par medicīnisko darba apģērbu [50], kam bija visdetalizētākā aprites cikla inventarizācija. Tas ir arī vienīgais pētījums, kurā iekļauti visi ražošanas procesi. Scenāriji veidoti bez ūdens emisijām, lai samazinātu nenoteiktību, jo tas būtu papildu nezināmais mainīgais. Turklāt tika izveidots scenārijs, izmantojot iebūvētos *Ecoinvent* procesus: sintētisko šķiedru aušanu, nepārtrauktu kokvilnas šķiedru krāsošanu un kokvilnas audumu apdari. Lai scenārijs būtu salīdzināms ar pārējiem, pārējie procesi tika izmantoti bez ūdens emisijām, taču jāpatur prātā, ka *Ecoinvent* procesos ir iekļautas emisijas.

Ietekmes kategorijas un ražošanas procesi

Pirmkārt, analizēts bāzes scenārijs, īpaši aplūkojot ražošanas procesu ietekmes sadalījumu. Aprites cikla ietekmes novērtējums sniedz rezultātus vairākām ietekmes kategorijām. Izvēlētajai metodei ir 18 ietekmes kategorijas, katrai no tām ir atbilstoša mērvienība. Tomēr, lai salīdzinātu kategorijas, ir jāpāriet uz kopēju mērvienību. To panāk normalizējot. Tas ir process, kurā tiek normalizētas ietekmes kategorijas vienā dimensijā un parādīti rezultāti plašākā kontekstā, kas norāda katras kategorijas ietekmi attiecībā pret kopējo ietekmi uz vidi [161]. Bāzes scenārija normalizētās vērtības ir redzamas 3.9. attēlā. Grafikā ir iekļautas visas kategorijas, kuru normalizētās vērtības ir lielākas par 0,0020, izņemot globālo sasilšanu (0,0016), kas arī tika iekļauta kā plaši izmantota kategorija ietekmes uz vidi novērtējumos. Jāpiebilst, ka rezultāti nav oriģināli, jo modeļa pamatā ir esošs pētījums [50]. Tomēr rezultāti netiek prezentēti un analizēti šādā veidā, tāpēc šādi novērojumi ir oriģināli.
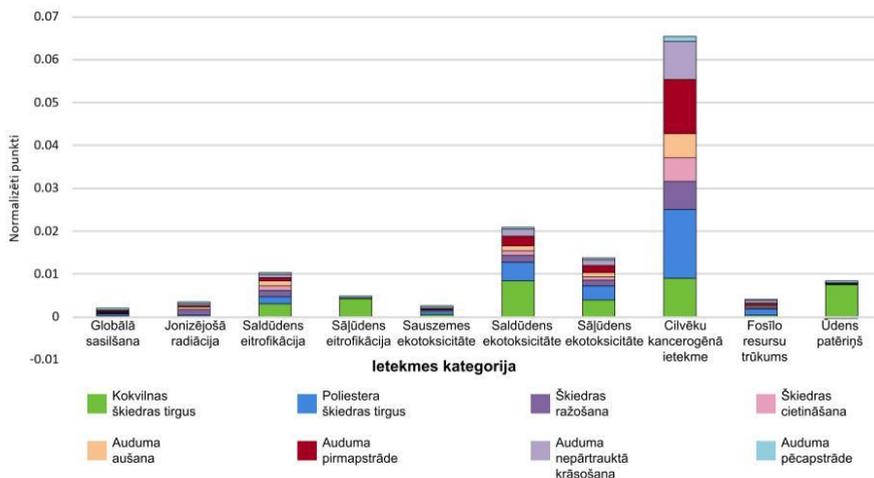
3.9. attēls. Normalizēti rezultāti pēc ietekmes kategorijām kokvilnas un poliestera maisījumu ražošanas bāzes scenārijam.

Var novērot, ka galvenās ietekmes kategorijas ir saistītas ar toksicitāti (cilvēka kancerogēnā toksicitāte, jūras ekotoksicitāte un saldūdens ekotoksicitāte), tāpēc ir svarīgi nodrošināt pilnīgu aprites cikla inventarizāciju, iekļaujot ķimikālijas, jo tās ir galvenais toksicitātes avots. No ievadītajām ķīmiskajām vielām vislielākā ietekme bija nātrija hidroksīdam, kas izskaidrojams ar izmantoto daudzumu, jo nātrija ditionītam ir vislielākā ietekme 4. scenārijā, kas balstīts uz publikācijā ietvertajiem uzņēmuma B05 datiem. Ir arī jāatzīmē, ka globālās sasilšanas kategorijai ir salīdzinoši neliela ietekme uz kopējo ietekmi uz vidi. Tas būtu jāņem vērā, analizējot tekstilizstrādājumu ekoloģiskos raksturlielumus. Aplūkojot iesaistīto procesu sadalījumu, vislielākā ietekme uz vidi ir izejvielu – kokvilnas un poliestera šķiedru – ieguvei, kam seko priekšapstrāde. Jāņem vērā, ka tas attiecas uz bāzes scenāriju, jo ietekmes sadalījums mainās, aplūkojot citus scenārijus. Atsauces pētījums uzrāda līdzīgus rezultātus [50], jo otra lielākā ietekme bija saistīta ar izejvielu ieguvi, savukārt pirmā bija saistīta ar izmantošanas fāzi, kas neietilpst šī pētījuma ietvaros.

Notekūdeņu nozīme

Viens no analīzes mērķiem bija noskaidrot, vai ūdens emisiju izslēgšana no aprites cikla inventarizācijas būtiski maina rezultātus. Tika izstrādāti divi bāzes scenāriji – ar un bez emisijām ūdenī. Pēc tam rezultāti tika salīdzināti savā starpā, un tika konstatēts, ka 11 no 18 ietekmes kategorijām bija vienādi rezultāti. Rezultāti būtiski atšķīrās sešās kategorijās, kas parādītas 3.10. attēlā. Šīm kategorijām ir vislielākā ietekme uz vidi salīdzinājumā ar pārējām, izņemot cilvēku nekancerogēnu toksicitāti, kas uzrāda vislielākās variācijas, bet nav tik ietekmīga kā pārējās. Turpretim 10 % atšķirību parāda cilvēka kancerogēnā toksicitāte, kurai ir vislielākā ietekme uz vidi no visām kategorijām. Kopumā šie rezultāti liecina, ka detalizētas

ūdens emisijas ir pamatoti iekļaut aprites cikla inventarizācijā, jo tās ietekmē galvenās ietekmes uz vidi kategorijas jauktās tekstilizstrādājumu ražošanas kontekstā.
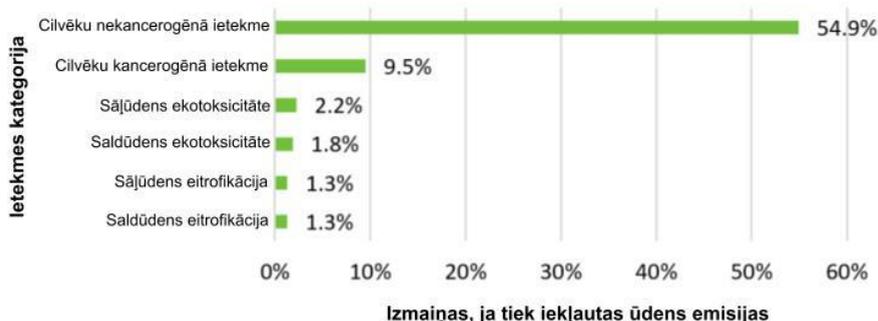
3.10. attēls. Rezultātu variācijas, iekļaujot detalizētas ūdens emisijas kokvilnas un poliestera maisījumu ražošanā.

Scenāriju salīdzinājums

Kā minēts iepriekš, šī pētījuma mērķis nav iegūt konkrētus skaitliskus rezultātus, bet gan aplūkot rezultātu atšķirības. Tāpēc katram scenārijam iegūtie rezultāti tika salīdzināti ar bāzes scenārijiem bez emisijām ūdenī un izteikti procentos. 3.11. attēlā ir apkopoti visu ietekmes kategoriju scenārijos iegūtie rezultāti.
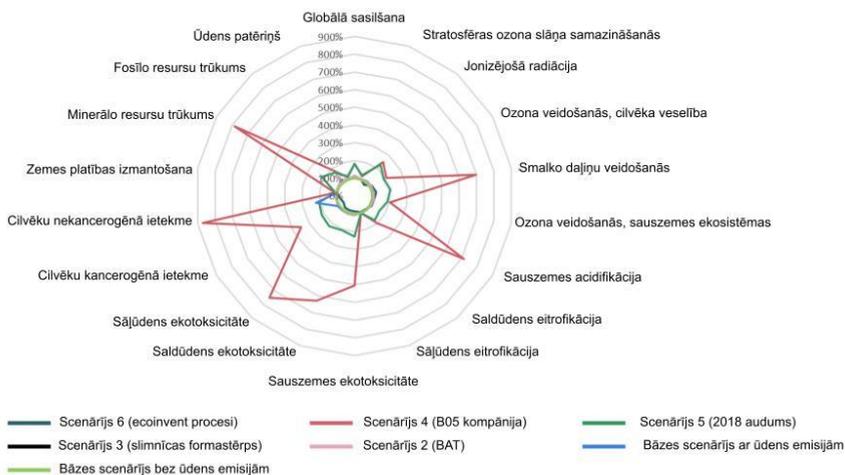
3.11. attēls. Rezultātu salīdzinājums pa ietekmes kategorijām, par atsauci izmantojot bāzes scenāriju bez ūdens emisijām.

2. un 3. scenārijs parāda vismazākās atšķirības no literatūrā balstītiem scenārijiem, salīdzinot ar bāzes scenāriju bez emisijām ūdenī, ar vidējām atšķirībām attiecīgi 6 % un 8 %.

Šie scenāriji ir balstīti uz LPTP un slimnīcas vienotu pētījumu [56], [162]. Nelielo atšķirību var izskaidrot ar to, ka avoti sniedz vismazāk datu par enerģiju un ūdeni, kas uzsver šo datu nozīmīgumu, un 3. scenārija pētījumā bija dati tikai par vienu no trim procesiem. Diagramma arī parāda, ka nevienam no literatūrā balstītajiem scenārijiem nav mazākas ietekmes uz vidi nekā bāzes scenārijam. Tas nozīmē, ka bāzes scenārijs ir labākais scenārijs attiecībā uz ietekmi uz vidi, vismaz saskaņā ar literatūrā pieejamajiem datiem. Tomēr tā pamatā ir kokvilnas ražošana, tāpēc to nevar uzskatīt par labāko variantu jauktu tekstilizstrādājumu novērtēšanai. 6. scenārijs ar *Ecoinvent* procesiem uzrādīja vidēji tikai 1 % atšķirību no bāzes līnijas, taču dažās kategorijās ietekme uz vidi bija mazāka. Tomēr rezultāts liecina, ka nav jāizdara lielāki pieņēmumi un jāpadara modelis vispārīgāks, izmantojot *Ecoinvent* iebūvētos procesus. Būtiskākās izmaiņas konstatētas 4. un 5. scenārijā ar vidēji 288 % un 81 %. 5. scenārija pamatā ir *Y. Zhang et al.* pētījums [163], kurā īpaši aplūkots CO/PES maisījums, bet izmantoti ierobežoti ievaddati. Šajā scenārijā tika mainītas tikai divas ķīmiskās vielas, bet gandrīz visas ūdens un enerģijas ievades tika mainītas, norādot, ka ūdens un enerģijas dati, visticamāk, bija atbildīgi par lielajām izmaiņām. 5. scenārijā, tāpat kā 4. scenārijā, tikai četras kategorijas ir relatīvi atbilstošas bāzes scenārijam – stratosfēras ozona noārdīšanās, jūras eitrofikācija, zemes izmantošana un ūdens patēriņš. Ūdens patēriņa kategorija būtiski nemainās, lai gan 5. scenārijā ūdens patēriņš palielinās, jo šīs kategorijas ietekmi galvenokārt nosaka kokvilnas ieguve. 4. scenārijā atšķirības svārstās no 3 % līdz 772 %. Šim scenārijam ir visvairāk izmaiņu ievades parametros. Nātrija ditionītam ir vislielākā ietekme, jo to izmanto ļoti lielos daudzumos salīdzinājumā ar bāzes scenāriju. Ņemot vērā, ka šī scenārija dati ir no 2003. gada [164], iespējams, ka lielas rezultāta izmaiņas rada novecojušas tehnoloģijas. Diagrammā redzami spēcīgi maksimumi astoņām kategorijām, kas pārsniedz 350 % atšķirību. Piecām no šīm kategorijām ir relatīvi nozīmīga ietekme uz vidi, 4. un 5. scenārijs parāda, ka rezultāti var ievērojami atšķirties, pamatojoties uz literatūrā pieejamajiem datiem, un uzsver nepieciešamību pēc īpašas DCI CO/PES maisījumiem.

3.3. Bibliometriskā analīze

3.3.1. Jaukto tekstilizstrādājumu bibliometriskās analīzes piemērs

ACN metodes piemērā tika aprakstīti ierobežojumi un pieņēmumi, kas ir izmantoti kokvilnas un poliestera maisījumu vides novērtējumos. Šajā gadījumā dati tika iegūti ar bibliometriskās analīzes palīdzību.

Rezultātā tika identificēts 31 atslēgvārds, kas tika lietots 12 vai vairākas reizes. Atslēgvārdi bija saistīti ar 278 saitēm un veidoja četras kopas. Atslēgvārdi un to saites ir parādītas 3.12. attēlā. Populārākais atslēgvārds bija atkritumi (36 gadījumi), kam sekoja tekstilizstrādājumi (35 gadījumi), pēc tam sekoja aprites cikla novērtējums un notekūdeņi (34 gadījumi). Aplūkojot kopējo saites stiprumu, secība bija līdzīga, izņemot otro spēcīgāko saikni, ko parāda ilgtspējība, kas norāda uz augstu korelāciju ar citiem vārdiem, lai gan sastopama mazāk nekā citi vārdi.

Vislielākā kopa bija ap atslēgvārdiem "notekūdeņi" un "degradācija", kas norāda, ka lielākā daļa pētījumu šajā jomā attiecas uz tekstilizstrādājumu notekūdeņiem un tekstilizstrādājumu dzīves beigām. Nākamais klasteris pēc lieluma bija ap atslēgvārdiem "atkritumi" un

"tekstilizstrādājumi", saistot tādus vārdus kā mehāniskā veiktspēja, parādot, ka tiek veikti pētījumi arī par jauktu tekstilizstrādājumu tehnisko pusi. Pēdējais būtiskais klasteris bija ap atslēgvārdu "aprites cikla novērtējums", kas nozīmē, ka tiek veikti pētījumi par jauktu tekstilizstrādājumu ietekmi uz vidi visā to dzīves ciklā, ņemot vērā ilgtspējības un aprites ekonomikas aspektus.

Svarīgs atklājums, ka aprites cikla novērtējums nav cieši saistīts ar notekūdeņiem, jo tas nav saistīts ar tādiem terminiem kā notekūdeņi, toksicitāte un smagie metāli. Tas liek domāt, ka esošajos ACN pētījumos par jauktiem tekstilizstrādājumiem, visticamāk, maz uzmanības tiks pievērsts notekūdeņiem un to toksiskajai iedarbībai. Tāpat neparādās ar siltumnīcefekta gāzēm saistīti atslēgvārdi, kas nozīmē, ka šis aspekts nav pietiekami izpētīts vai var nebūt būtisks, apsverot jaukta tekstila ietekmi uz vidi.

3.12. attēls. Atslēgvārdu līdzāsparādīšanās ar vismaz 12 atbilstību slieksni.

Kokvilnas un poliestera maisījumu ražošanas vides novērtējums

Tika izskatīti daudzi pārskata un oriģinālie pētījumi, pirms bija iespējams apkopot pētījumus par CO/PES ražošanas ietekmi uz vidi, kas attiecas uz šo pētījumu. Lielākā daļa no apskatītajiem pētījumiem tieši neattiecas uz CO/PES maisījumu ražošanu [52], [165], un izmanto vispārīgus datus [57], vai izmanto iepriekš izveidotus procesus no tādām datu bāzēm kā *Ecoinvent* [166], vai nesniedz detalizētus ievades datus [167]. Tika apstiprināts, ka literatūrā nav pieejama pilnīga CO/PES ražošanas aprites cikla inventarizācija (ACI). Tomēr tika atrasti vairāki pētījumi un ziņojumi ar datiem, kas daļēji aptver ražošanu (sk. 3.7. tabulu).

Pētījumi un ziņojumi, kas daļēji aptver datus par CO/PES ražošanas ietekmi uz vidi

Produkts	Materiāls	Iekļautie procesi	Iekļautie dati	Vispārīgs pieņēmums	Izdošanas gads	Avots
Medicīniskais darba apģērbs	CO/PES	dzijas vērpšana, cietināšana, aušana, pirmapstrāde, krāsošana un apdare	Ievade: enerģija, ūdens, ķīmiskās vielas. Izlaide: ūdens emisijas, atkritumi	Visi dati ņemti no kokvilnas ražošanas, izņemot dzijas vērpšanu	2023. gads	[50]
Audums	CO/PES	pirmapstrāde, krāsošana un apdare	Ievade: enerģija, ūdens, ķīmiskās vielas. Rezultāts: emisijas ūdenī, emisijas gaisā	Dati iegūti no komercsabiedrībām, taču netiek precizēts, kādi, ja tādi, pieņēmumi	2018. gads	[163]
Slimnīcas formas tērps	CO/PES	dzijas vērpšana, aušana, krāsošana un apdare	Ievade: enerģija, ūdens, ķīmiskās vielas. Rezultāts: emisijas ūdenī, emisijas gaisā, atkritumi	Izņemot izmēru noteikšanu un izmēru noņemšanu, un tikai krāsošana ir īpaši paredzēta CO/PES	2019. gads	[56]
Audums	CO/PES	pirmapstrāde, krāsošana	Ievade: enerģija, ūdens, ķīmiskās vielas. Rezultāts: ūdens emisijas	Dati ir no uzņēmuma pārskata, taču, iespējams, ir novecojuši	2003. gads	[164]
Audums (BAT)	CO un CO maisījumi	pirmapstrāde, krāsošana un apdare	Ievade: enerģija, ūdens, ķīmiskās vielas	Tiek pieņemts, ka kokvilnas un kokvilnas maisījumiem ir vienādi ievades parametri, izņemot apdares posmu	2023. gads	[162]

Vispilnīgākā inventarizācija par CO/PES ražošanu tika iekļauta V. Vāgnera u. c. ACN pētījumā [50]. Tajā ir iekļauti dati par primārajām izejvielām, piemēram, enerģiju un ūdeni, kas ir iekļauti vairākos pārskatītajos pētījumos. Tomēr tajā ir arī detalizēts izmantoto ķīmisko vielu saraksts un katra procesa notekūdeņu īpašības. Lai iegūtu pilnīgus datus, trūkst datu par emisijām gaisā. Tomēr galvenā problēma ir tā, ka visi dati tiek ņemti par kokvilnas ražošanu [168], jo autori atklāja, ka literatūrā nav pieejami dati par CO/PES ražošanu.

Literatūras apskats noveda pie pētījuma par CO/PES audumiem, kas ietvēra aprites cikla inventarizācija [163]. Pētījuma dati tiek vākti no uzņēmumiem, un tajos ir iekļauti dati par pirmapstrādi, krāsošanu un apdari. Aprites cikla inventarizācija (ACI) nodrošināja emisijas gaisā, kuras iepriekš nebija aplūkotas, taču ievades parametri un emisijas ūdenī ir ierobežotas. Tikai sārms (NaOH) un krāsvielas ir norādītas kā ievades ķīmiskās vielas. Datu iegūšana un pieņēmumi arī nav aprakstīti, tikai tas, ka dati iegūti no komercuzņēmumiem.

Datu trūkumu literatūrā par tekstilizstrādājumu ievades ķimikālijām atzina arī S. Rūss u. c., kurš veica pētījumu, lai izstrādātu ar tekstilizstrādājumu saistīto ķīmisko vielu nomenklatūras sistēmu, kas izmantota, lai izveidotu vispārīgu ķīmisko vielu sarakstu izmantošanai tekstilizstrādājumu aprites cikla novērtēšanai [56]. Tika apkopoti ACI dati par vairākiem galvenajiem tekstilizstrādājumu ražošanas procesiem un apkopoti ACI datu kopās. Turklāt ACI tika veikta arī dažiem tekstilizstrādājumiem. Viens bija slimnīcas formastērps, kas izgatavots no CO/PES maisījuma. Tomēr pētījumā tika aplūkots tikai viens process, kas īpaši paredzēts CO/PES maisījumam, – krāsošana. Tāpat netika iekļauta auduma cietināšana un atcietināšana, kurā pirmsaussāna un pirmapstrādes procesā tiek izmantotas daudzas ķīmiskas vielas [50].

Tā kā zinātniskajā literatūrā nebija pieejami citi pētījumi, kas ietvertu nepieciešamos datus, tika izskatīti dažādi ziņojumi. Turpmākai analīzei tika atlasīts uzņēmuma B05 ziņojums un tekstilrūpniecības ziņojuma labākās pieejamās metodes (BAT) [162], [164]. Uzņēmumam B05 tika ziņots par CO/PES auduma ražošanas ietekmi uz vidi [164]. Tika ziņots tikai par diviem procesiem, un nav pieejami detalizēti dati par emisijām. Turklāt ziņojums tika sagatavots 2003. gadā, un kopš tā laika ražošanas tehnoloģijas ir attīstījušās, tāpēc dati var būt novecojuši.

Atšķirībā no iepriekšējā gadījuma BAT ziņojumā ir apkopotas visas pašreizējās tendences tekstilrūpniecībā [162]. Tomēr tas nebija izņēmums, jo tekstilizstrādājumu maisījumiem tika pievērsts salīdzinoši maz uzmanības, un vairākos gadījumos tika pieņemts, ka kokvilnas un kokvilnas maisījumiem ir vienādi apstrādes un ražošanas procesi. Kvalitatīvāk tika aplūkotas arī tekstilizstrādājumu ražošanas radītās emisijas, un netika apkopoti konkrēti dati, kas sniegtu ieskatu tekstilrūpniecības ūdens un gaisa emisiju atsauces vērtībās.

Lai labāk izprastu atšķirības starp pētījumiem, tika analizēti katram pētījuma procesam specifiskie dati un pēc tam kopīgo parametru vērtības tika apkopotas 13. un 14. tabulā. Jāņem vērā, ka tie ir tikai kopīgie parametri, un tabulās nav parādīti citi ievades parametri katram gadījumam.

3.8. tabulā ir apkopotas ievades ķīmiskās vielas, kas pārklājas trīs procesos: pirmapstrādei, krāsošanai un apdarei. Dati par citiem procesiem nav iekļauti, jo tie bija uzskaitīti tikai vienā pētījumā [50]. Tika veikta pārslēgšanās uz tām pašām mērvienībām, lai varētu salīdzināt vērtības. Salīdzinot vērtības, var novērot, ka dažās vietās atšķirība ir neliela. Lielākā daļa variāciju ir ļoti lielas, piemēram, nātrija ditionīts un nātrija hidroksīds. Iespējams, tas ir saistīts

ar dažādiem apstrādes posmiem un tehnoloģijām, kas iesaistītas galvenajos procesos katrā situācijā, kā arī citu ievades ķīmisko vielu izslēgšanas dēļ, kas varētu izlīdzināt kopējo atšķirību. Jāņem vērā arī tas, ka nav pilnīgi pārklājošu parametru, kas norāda, ka visās procesa variācijās nav izmantotas būtiskas ķīmiskas vielas, kas iekļautas ACI.

3.8. tabula.

Datu, kas pārklājas, apkopošana no atlasītajiem pētījumiem un ziņojumiem (ķimikālijas)

	CO (medicīniskais darba apģērbs) [50], [168]	CO un CO/PES (BAT)* [162]	CO/PES (slimnīcas formas tērps) [56]	CO/PES (audums, uzņēmums B05)** [164]	CO/PES (audums) [163]
Iepriekšēja apstrāde					
Enzīmi, g kg⁻¹	4,8	5	–	–	–
Ūdeņraža peroksīds (H_2O_2), g kg⁻¹	35,4	10	–	65	–
Nejonu un jonu virsmaktīvā viela / mitrināšanas līdzekļi, g kg⁻¹	0,05	23,5	–	–	–
Nātrija hidroksīds (NaOH), g kg⁻¹	472,5	452	–	20	7000
Stabilizators, g kg⁻¹	–	5	–	25,3	–
Nātrija silikāts / mazgāšanas līdzeklis, g kg⁻¹	–	14	–	48	–
Krāsošana					
Nātrija ditionīts / nātrija hidrosulfīts , g kg⁻¹	2,4	–	–	3472	–
Ūdeņraža peroksīds (H_2O_2), g kg⁻¹	–	–	10	19,5	–
Nejonu un jonu virsmaktīvā viela/ Mitrināšanas līdzekļi, g kg⁻¹	0,02	108	4	–	–
Nātrija hidroksīds (NaOH), g kg⁻¹	65,3	–	12	42,5	–
Sekvestētāji, g kg⁻¹	–	144	6	–	–
Pretmigrācijas līdzeklis, g kg⁻¹	–	900	–	198,4	–
Etiķskābe/etiķis, g kg⁻¹	5	57,6	52	–	–
Vat krāsviela, g kg⁻¹	–	–	20	520,8	30
Reaktīvā krāsviela, g kg⁻¹	–	–	20	–	–
Dispersā krāsviela, g kg⁻¹	–	–	–	54,6	–
Apdare					
Mīkstinātājs, g kg⁻¹	16,2	920	–	–	–
Skābe/etiķskābe, g kg⁻¹	5,1	11,5	–	–	–

* Dažos gadījumos ķīmiskās vielas tika dotas kā gl⁻¹ ᵘᵈᵉⁿˢ, bet ūdens patēriņš netika nodrošināts, tāpēc, lai iegūtu g kg⁻¹ ūdens patēriņš tika ņemts no V. Vāgnera *u. c.* pētījums [50].
** Pētījumā vairākas ievades ķīmiskās vielas tika norādītas kā ml kg⁻¹, kuras tika pārveidotas par g kg⁻¹, izmantojot blīvumu.

Enerģijas un ūdens dati tika apkopoti tāpat kā ķīmiskajām vielām (sk. 3.9. tabulu). Atkal var novērot, ka ir gadījumi, kad atšķirības ir minimālas, piemēram, ūdens patēriņš apdarē, un ir arī ļoti būtiskas atšķirības, piemēram, ūdens un notekūdeņu priekšattīrīšanā. Vismazāk datu ir pieejami par siltumenerģiju. *Y. Zhang et al.* savā uzskaitē iekļāva izmantoto ogļu daudzumu, kas, visticamāk, tika izmantots apkurei, taču nepietiekamas informācijas dēļ tas netika iekļauts [163]. LPTP ziņojumā sniegti tikai vispārīgi dati par enerģijas un ūdens patēriņu tekstilrūpniecībā, bet nav datu par konkrētiem materiāliem un procesiem, izņemot ūdens patēriņu pirmapstrādes laikā [162].

3.9. tabula.

Datu, kas pārklājas, apkopošana no atlasītajiem pētījumiem un ziņojumiem
(enerģija un ūdens)

	CO (medicīniskais darba apģērbs) [50], [168]	CO un CO/PES (BAT) [162]	CO/PES (slimnīcas forma) [56]	CO/PES (audums, uzņēmums B05) [164]	CO/PES (audums) [163]
Iepriekšēja apstrāde					
Elektrība, kWh kg⁻¹	0,036	–	–	0,049	4
Ūdens, l kg⁻¹	–	23	–	23,24	616
Notekūdeņi, l kg⁻¹	15,10	–	–	20,40	350
Siltums, kWh kg⁻¹	0,16	–	–	–	–
Krāsošana					
Elektrība, kWh kg⁻¹	0,19	–	0,70	0,014	0,45
Ūdens, l kg⁻¹	72,72	–	75	24,80	12
Notekūdeņi, l kg⁻¹	33,35	–	–	19,50	–
Siltums, kWh kg -1	1,84	–	8,33	–	–
Apdare					
Elektrība, kWh kg⁻¹	0,16	–	–	–	0,31
Ūdens, l kg⁻¹	23,30	–	–	–	22,90
Notekūdeņi, l kg⁻¹	8,35	–	–	–	19,75
Siltums, kWh kg⁻¹	0,56	–	–	–	–

Pārskatītajos vides novērtējumos vismazāk iekļautie dati ir emisijas ūdenī un gaisā. Tas atbilst bibliometriskās analīzes secinājumam, ka ACN un notekūdeņi neuzrāda saistību. Tā tam nevajadzētu būt, jo, runājot par tekstilizstrādājumu ražošanas ietekmi uz vidi, liela uzmanība tiek pievērsta notekūdeņu toksicitātei [169]. Tāpēc ACN pētījumos jāiekļauj arī šis aspekts, lai pilnībā novērtētu jauktu tekstilizstrādājumu ietekmi uz vidi. Tikai pētījums par medicīnisko darba apģērbu ietver detalizētu tekstila notekūdeņu sastāvu, bet tas ņemts no kokvilnas ražošanas [50]. Citi pētījumi ietver tikai ķīmisko skābekļa pieprasījumu (ĶSP) [56], [163],

[164], kas ir nozīmīgākā sastāvdaļa pēc svara [169]. Tāpēc viens no turpmākās analīzes mērķiem ir noskaidrot, vai notekūdeņu izslēgšana būtiski ietekmē rezultātus.

Izmantojot literatūras analīzes datus, nav iespējams izstrādāt visaptverošu DCI CO/PES maisījuma tekstilizstrādājumiem, jo daži dati nav pieejami, pieejamo datu atšķirības ir pārāk lielas un pieņēmumi par procesiem un tehnoloģijām nav pilnībā skaidri. Tomēr tika veikts ACN, lai noskaidrotu, kā pieejamo datu atšķirības ietekmē CO/PES maisījumu ietekmes uz vidi rezultātus.

Ecoinvent procesi

Pēc literatūras apskata Ecoinvent datubāze tika pārbaudīta, lai novērtētu, vai ir pieejamas iebūvētās CO/PES ražošanas datu kopas. Datubāzē ir iekļauta tekstilizstrādājumu kategorija materiālu un procesu sadaļās, kas satur datu kopas par tekstilizstrādājumiem un to ražošanā un izmantošanā izmantotajiem procesiem. Materiālos nebija iekļauts CO/PES tekstilmateriāls, no kura būtu bijis iespējams redzēt ievaddatus tā ražošanai. Bija pieejamas kokvilnas un poliestera šķiedras, un tās tika tālāk izmantotas ACN modelēšanā.

Arī attiecībā uz procesiem nebija iebūvētu procesu, kas būtu īpaši paredzēts CO/PES maisījumam. Tomēr bija dažādi paņēmieni kokvilnai un poliesteram atsevišķi, lai gan ne visi. Piemēram, atkal trūka datu par izmēru noteikšanas procesu. Procesi, kurus varētu izmantot CO/PES modelēšanai ar pieņēmumiem, ir sintētisko šķiedru aušana, kokvilnas šķiedras nepārtrauktā krāsošana un kokvilnas audumu apdare.

3.3.2. Energopārvaldības bibliometriskās analīzes piemērs

Pēc līdzības kā bibliometriskā analīze tika piemērota jaukta tipa tekstilizstrādājumu izpētei, tomēr ar citu fokusu bibliometriskā analīzes lietojums energopārvaldībā izkristalizēja šī sektora rezultātus, kuri uzskatāmi parādīti 3.10. tabulā.

Vaicājumu iestatījumi un atslēgas vārdi.

Nr.	Vaicājuma iestatījums	Atslēgvārdi vaicājumā	Dokumentu skaits
		Vaicājums datubāzē SCOPUS	
1.	Paplašināts vaicājums visos laukos, visos publicētajos dokumentos laikposmā no 2009. līdz 2024. gadam	ALL ("energy audit") OR ALL ("energy auditing") AND PUBYEAR > 2008 AND PUBYEAR < 2025	9446
2.	Paplašināts vaicājums virsrakstā, anotācijā un atslēgvārdos, visos dokumentos, kas publicēti laikā no 2009. līdz 2024. gadam	TITLE-ABS-KEY ("Green Deal") OR TITLE-ABS-KEY ("fit for 55") AND PUBYEAR > 2008 AND PUBYEAR < 2025	3441
3.	Paplašināts vaicājums tikai virsrakstā, visos dokumentos, kas publicēti no 2009. līdz 2024. gadam	TITLE ("energy audit") OR TITLE ("energy auditing") AND PUBYEAR > 2008 AND PUBYEAR < 2025	631
4.	Paplašināts vaicājums tikai virsrakstā, visos dokumentos, kas publicēti no 2009. līdz 2024. gadam	TITLE ("energy audit") AND ALL ("energy efficiency") AND PUBYEAR > 2008 AND PUBYEAR < 2025	366
5.	Paplašināts vaicājums virsrakstā, anotācijā un atslēgvārdos, visos dokumentos, kas publicēti laikā no 2009. līdz 2024. gadam	TITLE-ABS-KEY ("Green Deal") OR TITLE-ABS-KEY ("fit for 55") AND PUBYEAR > 2008 AND PUBYEAR < 2025	321
6.	Paplašināts vaicājums tikai virsrakstā, visos dokumentos, kas publicēti no 2009. līdz 2024. gadam	TITLE ("energy efficiency first") OR TITLE ("energy efficiency first principle") AND PUBYEAR > 2008 AND PUBYEAR < 2025	17
		Vaicājumi datubāzē MDPI	
7.	Paplašināts vaicājums pilnteksta laukā, visos publicētajos dokumentos laika posmā no 2009. gada līdz 2024. gadam	FULLTEXT ("energy policies") AND FULLTEXT ("energy policy") AND "energy efficiency" With adding search filter for years between 2009–2024	3448
8.	Paplašināts vaicājums visos laukos, visos publicētajos dokumentos laikposmā no 2009. līdz 2024. gadam	ALL ("energy audit") OR ALL ("energy efficiency audit") AND "energy efficiency" With adding search filter for years between 2009–2024	821
9.	Paplašināts vaicājums tikai virsrakstā, visos dokumentos, kas publicēti no 2009. līdz 2024. gadam	TITLE ("energy audit") AND ALL ("energy efficiency") With adding search filter for years between 2009–2024	23
		Vaicājumi datubāze EUROPA SEARCH	
10.	Vaicājums visos laukos un visos formātos (Web, Word, PowerPoint, Excel, PDF)	Energy efficiency	6061

1.–9. vaicājumā tika izmantoti loģiskie operatori (UN, VAI), lai apvienotu terminus un nodrošinātu pilnīgus rezultātus. Loģiskie operatori atšķīra līdzīgu atslēgvārdu lietošanu, īpaši, ja atslēgvārdam ir alternatīvi termini. Loģiskais operators UN tika izmantots visos *SCOPUS* un *MDPI* vaicājumos, tādējādi ļaujot atrast dokumentus, kas attiecas gan uz energoauditu, gan energoefektivitāti, kā arī ļaujot noteikt laika ierobežojumu.

Papildu literatūra tika iegūta no valsts iestāžu tīmekļa vietnēm un uzņēmumiem, kas piedāvā energoaudita pakalpojumus (uzņēmumu piedāvājumi vai asociāciju tīmekļa vietnes). Šie dokumenti tika meklēti angļu vai latviešu valodā, meklējot tiesību aktus, un svarīgs aspekts bija to derīgums, kā arī grozījumu iekļaušana.

3.4. Sistēmdinamika

Modeļa bāzes gads bija 2018. gads, jo šis bija gads ar visvairāk pieejamajiem datiem. Galvenais mērķis bija noskaidrot, kā tuvākajā nākotnē mainīsies apglabājamo apģērbu apjoms, tāpēc tika modelēts bāzes scenārijs līdz 2030. gadam. Turklāt tika izveidoti četri scenāriji, lai aplūkotu politikas instrumentu ietekmi uz ierasto biznesu pieeju. Scenāriji ir apkopoti 3.13. attēlā.
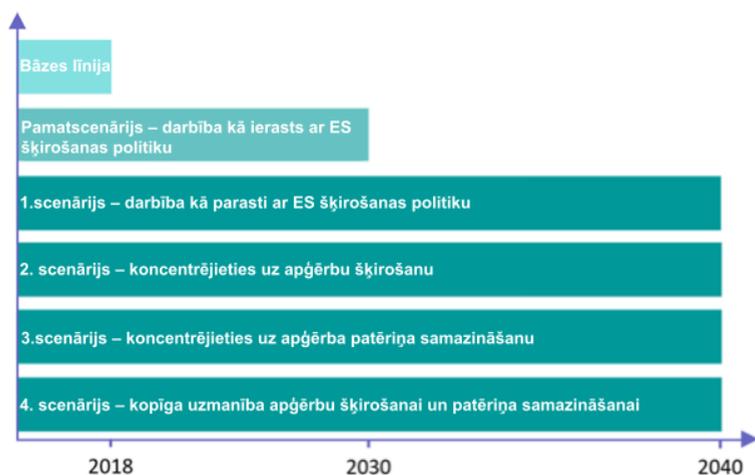
3.13. attēls. Izstrādāti un modelēti scenāriji un to laika intervāli.

Politikas instrumenti tika apvienoti visos iespējamos veidos, kā rezultātā tika izveidoti četri modelēšanas scenāriji. Politikas instrumenti sāk darboties tikai 2025. gadā, ņemot vērā, ka iepriekšējos gadus nevar ietekmēt, un ES tekstila atkritumu dalīto vākšanu ir noteikusi par obligātu no 2025. gada [42]. Lai politikas instrumenti varētu ietekmēt modeļa uzvedību, simulācija tika pagarināta līdz 2040. gadam. Pirmais scenārijs ir tāds pats kā bāzes scenārijs. Otrajā un trešajā scenārijā tiek aktivizēts tikai viens no politikas instrumentiem, savukārt ceturtajā scenārijā aktīvi ir abi politikas instrumenti. 3.11. tabulā parādītas iegūtās vērtības parametriem, kas sākotnēji tika definēti kā svarīgi aprites ekonomikas rādītāji dažādos scenārijos. Rezultāti ir sīkāk aprakstīti nākamajās apakšsadaļās.

Aprites ekonomikas galveno rādītāju vērtības tekstila nozarē dažādos scenārijos

	Bāze	Bizness kā parasti pēc ~10 gadiem	Bizness kā parasti pēc ~20 gadiem	Ar uzsvaru uz apģērbu šķirošanu	Ar uzsvaru uz patēriņa samazināšanu
Īpatnējais apģērbu patēriņš, kg/iedzīvotājs/gadā	9,8	16,0	24,1	24,1	5,0
Apģērba kalpošanas laiks, gadi	3,3	1,7	0,9	0,9	8,6
Tekstilizstrādājumu šķirošanas koeficients, %	38	33	31	81	100
Apģērbs, kas apglabāts izgāztuvē, miljoni tonnu gadā	3,3	5,8	8,9	5,1	0,7

Pamatscenārijs

Pamatscenārijs rāda, ka 2030. gadā izgāztuvēs tiks apglabāti 58 miljoni tonnu ES patērētā un saražotā apģērba. Ne viss no tiem tiek apglabāts ES izgāztuvēs, jo daļa tekstilizstrādājumu atkritumu tiek eksportēta [170]. Modelis parādīja, ka 2030. gadā, izmantojot biznesa kā ierasts pieeju, apģērbu patēriņš varētu būt 16 kg uz vienu iedzīvotāju, bet apģērba kalpošanas laiks varētu samazināties līdz 1,66 gadiem. Ikgadējā dzīves cikla SEG emisijas bija no 130 tCO_2 ekv/gadā līdz 212 miljoniem tCO_2 ekv/gadā. Attiecīgajā periodā kopumā tiktu radīti 2,13 miljardi t CO_2 ekv. Aptuvenais ES tekstilizstrādājumu šķirošanas apjoms 2018. gadā bija no 1,7 līdz 2,1 miljonam tonnu [66]. Sākotnējā apģērbu šķirošana modelī bija 1,67 miljoni tonnu. Rezultāti atbilst ES datiem, ņemot vērā, ka modes tekstilizstrādājumu daļa varētu būt aptuveni 81 % [66]. 3.14. attēlā parādīti simulācijas sākuma gada rezultāti un plūsmu sadalījums. Visas plūsmas ir norādītas tūkstošos tonnu gadā. Literatūrā ir piedāvāti dažādi tekstilmateriālu plūsmu varianti ES, taču līdz šim nebija pieejams detalizēts pārskats par apģērbu plūsmām.
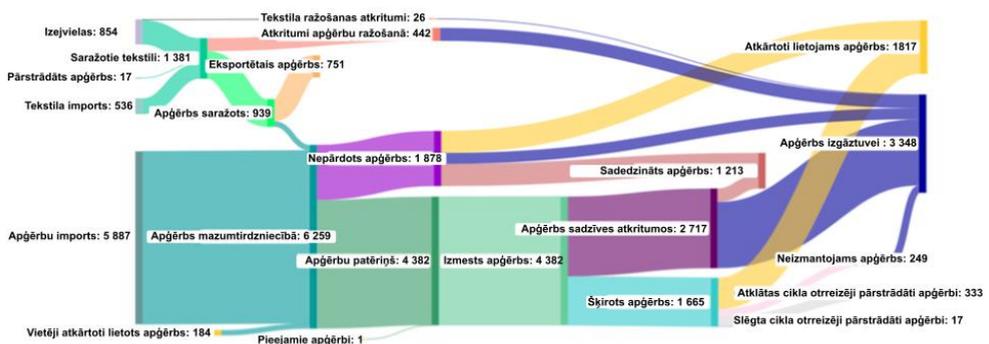
3.14. att. Materiālu plūsmas ES modes tekstilizstrādājumu vērtību ķēdē 2018. gadā (tūkst. tonnu /gadā).

Materiālu plūsmas modes tekstila vērtību ķēdē ES 2030. gadā ir parādītas 3.15. attēlā. Redzams, ka visu plūsmu vērtības ir pieaugušas, kas atbilst prognozēm. Tā kā bāzes scenārijā bija iekļauta šķirošanas jaudas palielināšana, tika prognozēts, ka apģērbu šķirošanas īpatsvars palielināsies. Kā redzams 3.14. un 3.15. attēlā, vizuāli plūsmu attiecība nav būtiski mainījusies. To apliecina arī šķirošanas ātruma skaitliskā vērtība. 2018. gadā apģērbu šķirošanas rādītājs bija 38 %, savukārt iegūtais 2030. gada šķirošanas rādītājs bija 33 %. Šķirošanas ātrums ir samazinājies, jo konstatētais šķirošanas jaudas pieaugums ir proporcionāli mazāks nekā patēriņa un izmestā apģērba pieaugums.
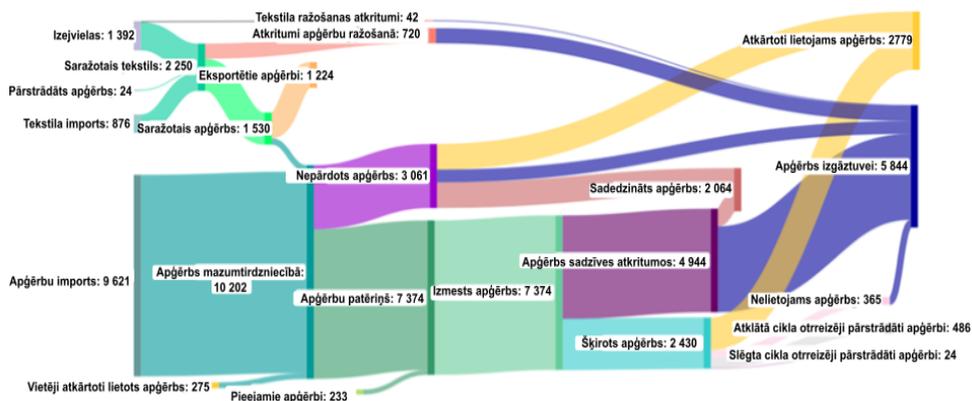
3.15. att. Materiālu plūsmas ES modes tekstilizstrādājumu vērtību ķēdē 2030. gadā
(tūkst. tonnu /gadā).

Pirmais scenārijs – bāzes scenārijs līdz 2040. gadam

Pirmais scenārijs ir tāds pats kā bāzes scenārijs, izņemot to, ka simulācijas periods ir pagarināts līdz 2040. gadam. Tas tiek uzskatīts par ierasto situāciju, jo vienīgā modelī iekļautā politika ir ES prognoze par šķirošanas pieauguma tempu. Tika pieņemts, ka pēdējo desmit gadu tendences ir tādas pašas kā līdz 2030. gadam. Atkritumos apglabāto apģērbu rezultātā tika saražoti 130 miljoni tonnu. SEG emisijas 2040. gadā sasniedza 319 miljonus t CO$_2$ ekv./gadā.

Otrais scenārijs – apģērbu šķirošanas politika

Otrais scenārijs parāda gadījumu, kad politikas mērķi modes tekstilizstrādājumu vērtību ķēdē ir vērsti tikai uz šķirošanas jaudas palielināšanu. Poligonā apglabāto apģērbu apjoms sasniedza 105 miljonus tonnu. Apģērbu šķirošanas īpatsvars pieauga līdz 81 %. SEG emisijas 2040. gadā salīdzinājumā ar pirmo bāzes scenāriju nedaudz samazinājās līdz 310 miljoniem t CO$_2$ ekv./gadā.

Apģērbu šķirošanas politikas aktivizēšana radīja līdzsvarošanas cilpu, kas redzama 3.16. attēlā. Attēlā parādīti tikai visatbilstošākie cēloņsakarības cilpas elementi. Pirmajā saitē norādīts, ka, palielinoties izgāztuvēs noglabāto apģērbu apjomam, palielinās arī atbalsta īpatsvars šķirošanai. Jo augstāks šķirošanas atbalsts, jo lielāka šķirošanas jauda darbībā, kas

vienāda ar šķirotajām drēbēm. Līdzsvarošanas cilpa veidojas, jo palielinās sašķiroto apģērbu apjoms, un samazinās sadzīves atkritumos esošo apģērbu apjoms.
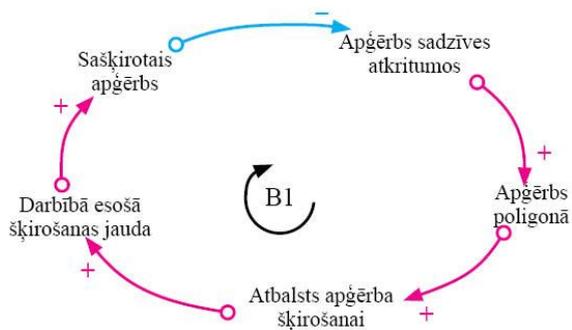
3.16. attēls. Apģērbu šķirošanas politikas cēloņsakarības diagramma.

Trešais scenārijs – patēriņa samazināšanas politika

Trešajā scenārijā politikas mērķi modes tekstilizstrādājumu vērtību ķēdē ir vērsti tikai uz apģērbu patēriņa samazināšanu. Politikas instruments vājina pozitīvo cilpu starp īpašo apģērbu patēriņu un patēriņa izmaiņām. Apģērbu apglabāšana izgāztuvēs sasniedza 69 miljonus tonnu. Tiek sasniegts ievērojami lielāks samazinājums nekā otrajā scenārijā (apģērbu šķirošanas politika), un drēbes tiek pilnībā sašķirotas 2033. gadā, jo bāzes scenārija šķirošanas jaudas pieaugums ir pietiekams, lai nodrošinātu pilnīgu izmesto apģērbu šķirošanu. SEG emisijas ir arī ievērojami samazinātas līdz 64 miljoniem t CO_2 ekv./gadā 2040. gadā.

Tika prognozēts, ka apģērbu patēriņa rādītājs pieaugs, pārsniedzot prognozes, un pēc tam strauji samazināsies. Rezultātā novērotā tendence atbilda prognozēm. Apģērbu patēriņš 2028. gadā sasniedza 14,5 kg uz vienu iedzīvotāju, pēc tam strauji samazinājās līdz 5 kg uz vienu iedzīvotāju, kas tika noteikts kā minimālā vērtība. Apģērbu patēriņa samazināšanas politikas uzsākšana radīja divas līdzsvarošanas cilpas, kā parādīts 3.17. attēlā. Galvenais elements ir īpatnējais apģērbu patēriņš, kas politikas instrumenta gadījumā ir atkarīgs no radīto emisiju apjoma. Lielajā negatīvajā cilpā pirmā saite norāda, ka maksimālais pieejamais emisiju daudzums samazinās, palielinoties emisijām. Jo mazākas emisijas var rasties modes tekstilizstrādājumu vērtību ķēdē, jo lielāka ietekme uz zaudējumu daļu, kas samazina apģērba īpatnējo patēriņu. Apģērba īpatnējais patēriņš nosaka radīto izmešu daudzumu. Papildus veidojas balansēšanas cilpa, kas stabilizē īpatnējo apģērba patēriņu, kad tas ir samazinājies.
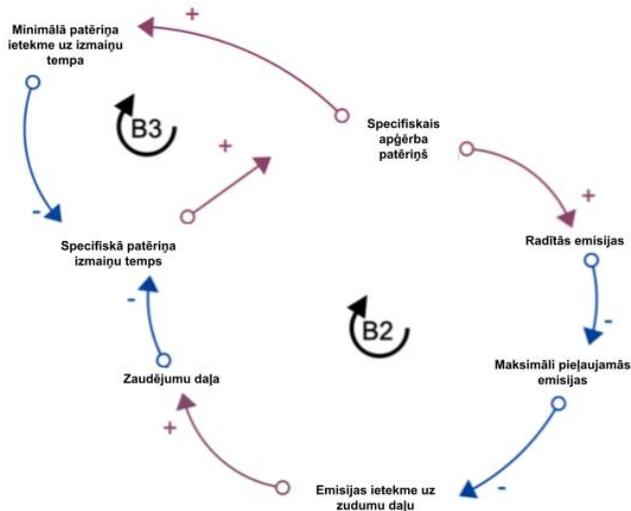
3.17. attēls. Apģērba patēriņa samazināšanas politikas cēloņsakarības diagramma.

Ceturtais scenārijs – patēriņa samazināšanas politika un apģērbu šķirošanas politika

Abi politikas instrumenti tika aktivizēti ceturtajā scenārijā, tāpēc visas trīs iepriekš aprakstītās cēloņsakarības bija aktīvas. Šis scenārijs ir labākais, jo izgāztuvēs apglabāto apģērbu apjoms sasniedza 65 miljonus tonnu, kas ir uz pusi mazāks nekā pirmajā bāzes scenārijā līdz 2040. gadam. SEG emisijas 2040. gadā bija tādas pašas kā trešajā scenārijā (patēriņa samazināšanas politika).

Visi apģērbi tiks šķiroti līdz 2032. gadam. Rezultāti liecina, ka šķiroti apģērbi, sasniedzot šķirošanas rādītāju „1", rīkojas tāpat kā izmesti apģērbi, jo nav iespējams šķirot vairāk apģērbu, nekā tiek izmesti. Tas rada neizmantotu šķirošanas jaudu, jo tā nevar tik ātri pielāgoties izmestu apģērbu daudzuma samazinājumam. Šo lieko jaudu var izmantot citu tekstilizstrādājumu šķirošanai.

Darbību salīdzinājums parādīts 3.18. attēlā. Labākais scenārijs ir ceturtais. Tajā pašā laikā visefektīvākais politikas instruments ir **Patēriņa samazināšanas politika**, jo tā atbilst tādai pašai tendencei kā 4. scenārijā. Tā ir arī vēlamā bāzlīnija: izgāztuvēs apglabāto apģērbu daudzums sāk pieaugt daudz lēnāk, taču tas joprojām palielinās. nedaudz, jo šķiroto apģērbu plūsmā ir arī piesārņots apģērbs, ko nevar pārstrādāt vai izmantot atkārtoti, un scenārijos nav ņemta vērā atkārtota izmantošana, pārstrāde vai izvairīšanās no ražošanas un pārdošanas pārpalikumiem, kas ietekmē arī poligonā nonākušo tekstilizstrādājumu daudzumu.
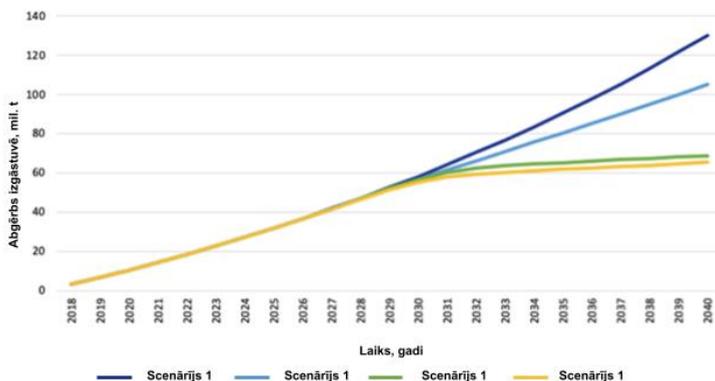
3.18. attēls. Bāzes uzvedības izmaiņu salīdzinājums modelētajos scenārijos.

Plūsmas 2040. gadā, kas izriet no ceturtā scenārija, ir parādītas 3.1.9. attēlā. Sadzīves atkritumu plūsmas nav, bet apģērbu apglabāšana poligonos joprojām notiek. Nozīmīgākā plūsma vērtību ķēdes beigās ir atkārtoti lietots apģērbs. *Sankey* diagramma norāda arī uz citiem aktuāliem jautājumiem, kuriem jāpievērš uzmanība, piemēram, lietotu apģērbu eksportu un to neizmantošanu mājsaimniecībā, rūpniecisko un komerciālo atkritumu apglabāšanu poligonos un joprojām ļoti zemo slēgtā cikla otrreizējās pārstrādes īpatsvaru. Tāpat kā iepriekš, plūsmas uzrādītas tūkstošos tonnu gadā.
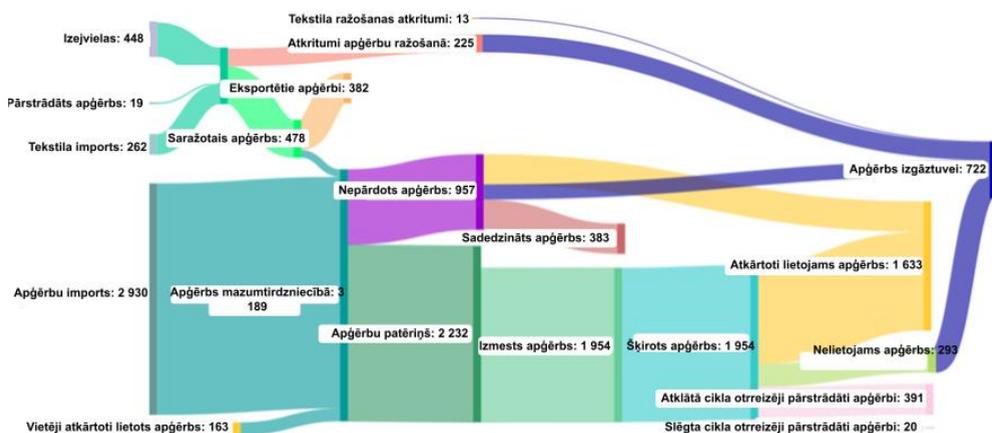
3.19. attēls. Materiālu plūsmas ES modes tekstila vērtību ķēdē
2040. gadā no 3. un 4. scenārija (tūkst. tonnu /gadā).

3.5. Izplūdusī kognitīvā karte (*FCM*)

Pētījumā "Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps" tika aprakstīts citronskābes ražošanas procesa modelis un iegūtie rezultāti. Tādā pašā veidā tika analizēti visi 16 ražošanas procesi, lietojot analoģisku

modelēšanas veidu un identiskus kritērijus. Tomēr, kā minēts iepriekš, pētījuma galvenais mērķis ir iegūt datus, lai izvēlētos no aprakstītajiem ražošanas procesiem primāri izveidotos un tos sarindotu, tādējādi nosakot, kurš no piedāvātajiem risinājumiem ir visefektīvākais un pierāda pievienoto vērtību bioekonomikas skatījumā uz Zaļā kursa mērķu sasniegšanu. Lai iegūtu šādu rezultātu, katra ražošanas procesa rezultāts sadaļā "ražošanas procesa efektivitāte" tiek salīdzināts savā starpā pēc iegūtā kvantitatīvā rezultāta skalā līdz 1 (3.12. tabula). Uzskaitītie rezultāti ir parādīti stabiņu diagrammā 3.20. attēlā.

Diagramma (3.20. attēls) parāda 16 ražošanas procesu iegūtos kvantitatīvos rezultātus lietderības salīdzinājumā. Iegūtie rezultāti rāda, ka visefektīvākais ražošanas process ir kompozītmateriālu ražošana. Šo rezultātu pamato izejvielu pieejamība kompozītmateriāliem, kas galvenokārt ir citu ražošanas procesu blakusprodukti: zemas kvalitātes koksnes atlikumi un pārstrādāta plastmasa. Tāpat arī pieprasījums pēc šādiem kompozītmateriāliem tirgū strauji pieaug to fizikālo īpašību dēļ, ražošanas tehnoloģijas ir salīdzinoši vienkāršas un pieejamas bez pārmērīgiem ieguldījumiem. Neiedziļinoties katra ražošanas procesa pozitīvajās īpašībās, kas aprakstīto ražošanas procesu ir pietuvinājušas iegūtajam augstajam rezultātam, secinām, ka 11 no aprakstītajiem 16 ražošanas procesiem ir sasnieguši ļoti augstas vērtības diapazonā no 0,9 līdz 1, un visi 11 ražošanas procesi atbilst augstai bioekonomikas efektivitātei Zaļā kursa mērķu sasniegšanai, tādējādi šie ražošanas procesi ir ļoti vērtīgi un būtu primāri jāievieš ekonomikā, ieguldot ražošanas iekārtās.

3.12. tabula.

Ražošanas procesa lietderība

Citronskābes ražošana	0,97
Sudraba nanodaļiņu sintēze	0,96
Kompozītmateriālu ražošana	0,98
Nanoceluloze ražošana	0,92
Tualetes ūdens ražošana no sūkalām	0,97
Ksilāna ražošana	0,92
Polikaktīda ražošana	0,97
Nātres šķiedru izmantošana ražošanā	0,29
Biodīzeļdegvielas ražošana	0,73
"*DendroLight*" šūnu materiāla ražošana	0,98
Granulu ražošana	0,83
Bioetilēna ražošana	0,68
Celulozes ražošana	0,94
Putu ražošana uz tanīnu bāzes	0,9
Skujkoku ekstrakta ražošana	0,96
Lignīna ražošana	0,83
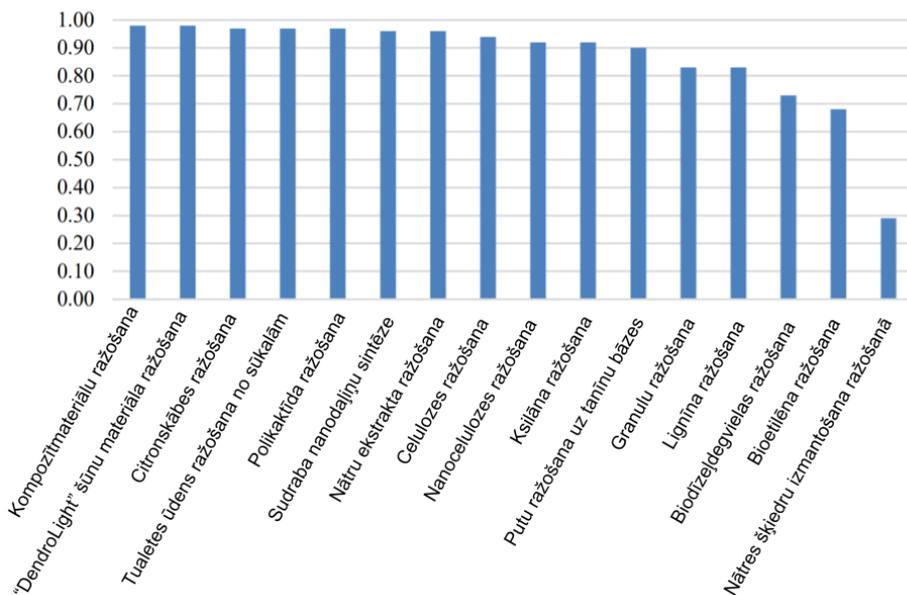
3.20. attēls. Ražošanas procesu lietderības kopsavilkums.

Pretstatā tam, biodīzeļdegvielas un bioetilēna ražošanas procesi, lai gan ļoti vērtīgi fosilā kurināmā aizstāšanai un naftu neražojošo valstu neatkarības palielināšanai no fosilajiem resursiem, joprojām ir ļoti tehnoloģiski sarežģīti un prasa milzīgus ieguldījumus to ražošanā, kas pašlaik samazina to ražošanas ekonomisko dzīvotspēju. Tomēr straujā zinātnes un tehnoloģiju attīstība neizbēgami tuvākajā desmitgadē tuvinās biodīzeļdegvielas un bioetilēna ražošanu.

Vājākais rezultāts (0,29 no 1) tika iegūts dabisko nātru šķiedru ražošanā. Šis rezultāts ir saistīts ar šī ražošanas procesa konkurenci par lauksaimniecības zemi ar pārtikas rūpniecību un iegūtā produkta zemo konkurētspēju tekstilrūpniecībā, jo būtu ļoti grūti pamatot nātru ražošanu lielās platībās un to pārstrādi tekstilizstrādājumos no vides un ekonomikas viedokļa.

Ņemot vērā pētījuma mērķus, iegūtie rezultāti ir uzticami un objektīvi atspoguļo *FCM* metodes derīgumu, un šāda veida integrētās analīzes izmantošana ir piemērota, lai salīdzinātu dažādus alternatīvos ražošanas procesus, kas apskatīti darbā.

SECINĀJUMI

1. Lai gan promocijas darbā ir izvērtēti ļoti daudz un dažāda veida atkritumu pārstrādes vai produkta ar augstāku pievienoto vērtību ražošanas procesi, tomēr, balstoties uz vairāku pētīju rezultāties, sevišķi pētījuma "What Drives the Circular Economy? Textile Sorting or Consumption Reduction" rezultātiem secināms, ka nemainīgi pirmais solis ceļā uz aprites ekonomiku ir patēriņa samazināšanas politika, tādējādi apstiprinot promocijas darbā izvirzīto hipotēzi.

2. Lēmumu izstrādes un pieņemšanas procesā izmantojot zinātniskās pētniecības metodes, var kompleksi izvērtēt labākos iespējamos scenārijus un ilgtspējīgas izvēles aprites ekonomikas ieviešanai, jo ne visus aspektus var izvērtēt tikai ar vienu metodi. Veidojot metožu kopumu vai kombināciju kā rīku sistēmu, ir iespējams visaptveroši un datos balstīti izvērtēt katra ražošanas vai pārstrādes procesa potenciālu aprites ekonomikas attīstībai.

3. Pētījuma laikā veiktā Sistēmdinamikas analīze kas nodrošina stratēģijas formulēšanu, politikas izstrādi un lēmumu pieņemšanu sarežģītās un dinamiskās jomās ļāva secināt, ka šobrīd Latvijas, kā arī citu valstu politikas veidotājiem ir svarīgi veikt esošo vai plānoto aprites ekonomikas stratēģiju efektivitātes novērtējumu, lai izstrādātu īstermiņa un ilgtermiņa rīcības plānus, kas ne tikai veicinātu pāreju uz aprites ekonomikas modeli, bet arī nodrošinātu saprātīgus praktiskus risinājumus, tostarp politkas atbalstu un papildu finanšu instrumentus, tādējādi stimulējot uzņēmumus investēt ilgtspējīgā aprites ekonomikas rūpniecībā.

4. Ņemot vērā pētījuma mērķus, iegūtie rezultāti ir uzticami un objektīvi atspoguļo lietoto zinātnisko metožu kombinēšanas nozīmīgumu. Šāda veida integrētās analīzes izmantošana ir piemērota, lai salīdzinātu dažādus alternatīvus ražošanas procesus, kas apskatīti darbā.

5. Promocijas darbā iegūtie rezultāti apliecina, ka jebkura atkritumu, atlikumu vai blakusproduktu pārstrāde mazina ietekmi uz klimatu, nodrošina ceļu uz ilgtspējīgu attīstību un veicina produktu ar augstāku pievienoto vērtību attīstību.

REKOMENDĀCIJAS

1. Veidot papildu atbalsta instrumentus pētniecības iestādēm, atbalstot zinātnē balstītu metožu un rīku izstrādi aprites ekonomikas rīcības plāna attīstībai.

2. Likumdevēju varas iestādēm strādāt pie politiskajiem risinājumiem, lai veicinātu uzņēmēju interesi investēt atkritumu kā resursa izmantošanai produktu ar augstāku pievienoto vērtību ražošanai.

3. Nevalstiskajām organizācijām popularizēt sabiedrībai patēriņa samazināšanas nozīmīgumu un tā ietekmi uz vides aspektiem.

4. Latvijas politikas veidotājiem ir svarīgi izvērtēt esošās aprites ekonomikas stratēģijas efektivitāti gan īstermiņā, gan ilgtermiņā, kas veicinātu pāreju uz aprites ekonomiku un nodrošinātu praktiskus risinājumus, piemēram, politikas atbalstu, finansiālus stimulus un uzraudzību.

5. Valsts pārvaldes iestādēm, kuras ir atbildīgas par ekonomikas, labklājības un vides aizsardzības jomām, cieši jāsadarbijas, lai izstrādātu vadlīnijas uzņēmumiem par aprites ekonomikas praktiskajiem aspektiem un elementiem, kā pāriet no lineārās ekonomikas uz aprites ekonomikas biznesa modeļiem.

ATSAUCES

[1] K. Shirvanimoghaddam, B. Motamed, S. Ramakrishna, and M. Naebe, "Death by waste: Fashion and textile circular economy case," *Science of The Total Environment*, vol. 718, p. 137317, 2020, doi: 10.1016/J.SCITOTENV.2020.137317.

[2] Ellen MacArthur Foundation, "A new textiles economy: Redesigning fashion's future." [Online]. Available: https://emf.thirdlight.com/file/24/uiwtaHvud8YIG_uiSTauTlJH74/A New Textiles

[3] S. Yasin and D. Sun, "Propelling textile waste to ascend the ladder of sustainability: EOL study on probing environmental parity in technical textiles," *Journal of Cleaner Production*, vol. 233, pp. 1451–1464, Oct. 2019, doi: 10.1016/j.jclepro.2019.06.009.

[4] J. P. Juanga-Labayen, I. V Labayen, and Q. Yuan, "A Review on Textile Recycling Practices and Challenges," *Textiles 2022, Vol. 2, Pages 174-188*, vol. 2, no. 1, pp. 174–188, 2022, doi: 10.3390/TEXTILES2010010.

[5] Earth Overshoot Day, "Past Earth Overshoot Days." [Online]. Available: https://www.overshootday.org/newsroom/past-earth-overshoot-days/

[6] J. Tomaszewska, "Polish Transition towards Circular Economy: Materials Management and Implications for the Construction Sector," *Materials*, vol. 13, no. 22, p. 5228, Nov. 2020, doi: 10.3390/ma13225228.

[7] European Commission, "A new Circular Economy Action Plan." [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[8] United Nations, "The 2030 Agenda for Sustainable Development." [Online]. Available: https://www.un.org/sustainabledevelopment/development-agenda/

[9] European Environment Agency, "Textiles and the environment: the role of design in Europe's circular economy." [Online]. Available: https://www.eea.europa.eu/publications/textiles-and-the-environment-the

[10] A. Sharma, R. Lakshmanan, and M. Nayyar, "Technical Textiles: The Future of Textiles." [Online]. Available: https://www.investindia.gov.in/siru/technical-textiles-future-textiles

[11] B. Zlaugotne, L. Zihare, L. Balode, A. Kalnbalkite, A. Khabdullin, and D. Blumberga, "Multi-Criteria Decision Analysis Methods Comparison," *Environmental and Climate Technologies*, vol. 24, no. 1, pp. 454–471, Jan. 2020, doi: 10.2478/rtuect-2020-0028.

[12] G. M. Acar E., Kiliç M., "Measurement of sustainability performance in textile industry by using a multi-criteria decision making method.," Textile and Apparel. [Online]. Available: https://dergipark.org.tr/en/pub/tekstilvekonfeksiyon/issue/23647/251904

[13] F. Jia, S. Yin, L. Chen, and X. Chen, "The circular economy in the textile and apparel industry: A systematic literature review," *Journal of Cleaner Production*, vol. 259, p. 120728, 2020, doi: 10.1016/J.JCLEPRO.2020.120728.

[14] M. M. Wagner and T. Heinzel, "Human Perceptions of Recycled Textiles and Circular Fashion: A Systematic Literature Review," *Sustainability 2020, Vol. 12, Page 10599*, vol. 12, no. 24, p. 10599, 2020, doi: 10.3390/SU122410599.

[15]   S. Moazzem, L. Wang, F. Daver, and E. Crossin, "Environmental impact of discarded apparel landfilling and recycling," *Resources, Conservation and Recycling*, vol. 166, p. 105338, Mar. 2021, doi: 10.1016/j.resconrec.2020.105338.

[16]   R. Aus, H. Moora, M. Vihma, R. Unt, M. Kiisa, and S. Kapur, "Designing for circular fashion: integrating upcycling into conventional garment manufacturing processes," *Fashion and Textiles*, vol. 8, no. 1, pp. 1–18, 2021, doi: 10.1186/S40691-021-00262-9/FIGURES/7.

[17]   M. De Saxce, S. Pesnel, and A. Perwuelz, "LCA of bed sheets – some relevant parameters for lifetime assessment," *Journal of Cleaner Production*, vol. 37, pp. 221–228, Dec. 2012, doi: 10.1016/j.jclepro.2012.07.012.

[18]   L. Ranasinghe and V. M. Jayasooriya, "Ecolabelling in textile industry: A review," *Resources, Environment and Sustainability*, vol. 6, p. 100037, 2021, doi: 10.1016/J.RESENV.2021.100037.

[19]   C. Montanari, P. Olsén, and L. A. Berglund, "Sustainable Wood Nanotechnologies for Wood Composites Processed by In-Situ Polymerization," *Frontiers in Chemistry*, vol. 9, Jul. 2021, doi: 10.3389/fchem.2021.682883.

[20]   D. Blumberga, "Forest biomass – new products and technologies.," 2016, *Riga Technical University, Institute of Energy Systems and Environment, Riga*.

[21]   V. Terjanika and J. Pubule, "Barriers and Driving Factors for Sustainable Development of CO2 Valorisation," *Sustainability*, vol. 14, no. 9, p. 5054, Apr. 2022, doi: 10.3390/su14095054.

[22]   V. Terjanika, J. Gusca, J. Pubule, and D. Blumberga, "Analysis of CO 2 Valorisation Options for Regional Development," *Environmental and Climate Technologies*, vol. 25, no. 1, pp. 243–253, Jan. 2021, doi: 10.2478/rtuect-2021-0017.

[23]   V. Terjanika, D. Blumberga, and J. Pubule, "Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia," in *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, IEEE, Nov. 2021, pp. 1–5. doi: 10.1109/RTUCON53541.2021.9711727.

[24]   T. Singh *et al.*, "Emerging technologies for the development of wood products towards extended carbon storage and CO2 capture," *Carbon Capture Science & Technology*, vol. 4, p. 100057, Sep. 2022, doi: 10.1016/j.ccst.2022.100057.

[25]   X. Xu, P. Xu, J. Zhu, H. Li, and Z. Xiong, "Bamboo construction materials: Carbon storage and potential to reduce associated CO2 emissions," *Science of The Total Environment*, vol. 814, p. 152697, Mar. 2022, doi: 10.1016/j.scitotenv.2021.152697.

[26]   N. Tripathi, C. D. Hills, R. S. Singh, and C. J. Atkinson, "Biomass waste utilisation in low-carbon products: harnessing a major potential resource," *npj Climate and Atmospheric Science*, vol. 2, no. 1, p. 35, Oct. 2019, doi: 10.1038/s41612-019-0093-5.

[27]   V. Kazulis, I. Muizniece, L. Zihare, and D. Blumberga, "Carbon storage in wood products," *Energy Procedia*, vol. 128, pp. 558–563, Sep. 2017, doi: 10.1016/j.egypro.2017.09.009.

[28]   K. Raunkjaer Stubdrup, "Best Available Techniques (BAT) Reference Document for the Production of Woodbased Panels," 2016, *JRC, Seville*.

[29]   K. Veitmans and U. Grinfelds, "Wood fibre insulation material.," 2016, *Research for Rural Development*.

[30]   I. Vamza, A. Kubule, L. Zihare, K. Valters, and D. Blumberga, "Bioresource utilization index – A way to quantify and compare resource efficiency in production," *Journal of Cleaner Production*, vol. 320, p. 128791, Oct. 2021, doi: 10.1016/j.jclepro.2021.128791.

[31]   A. Younis and A. Dodoo, "Cross-laminated timber for building construction: A life-cycle-assessment overview," *Journal of Building Engineering*, vol. 52, p. 104482, 2022, doi: 10.1016/j.jobe.2022.104482.

[32]   M. F. L. Mallo and E. Omar, "Cross-Laminated Timber Vs. Concrete/Steel: Cost Comparison Using A Case Study," in *the WCTE2016 World Conference on Timber Engineering*, Vienna, Austria, 2017.

[33]   T. Singh *et al.*, "Emerging technologies for the development of wood products towards extended carbon storage and CO2 capture," *Carbon Capture Science & Technology*, vol. 4, p. 100057, 2022, doi: 10.1016/j.ccst.2022.100057.

[34]   A. Jayalath, S. Navaratnam, T. Ngo, P. Mendis, N. Hewson, and L. Aye, "Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia," *Energy and Buildings*, vol. 223, p. 110091, 2020, doi: 10.1016/j.enbuild.2020.110091.

[35]   I. Vamza, K. Valters, I. Luksta, P. Resnais, and D. Blumberga, "Complete Circularity in Cross-Laminated Timber Production," *Environmental and Climate Technologies*, vol. 25, no. 1, pp. 1101–1113, 2021, doi: 10.2478/rtuect-2021-0083.

[36]   C. K. de Carvalho Araújo *et al.*, "Life cycle assessment as a guide for designing circular business models in the wood panel industry: A critical review," *Journal of Cleaner Production*, vol. 355, p. 131729, Jun. 2022, doi: 10.1016/j.jclepro.2022.131729.

[37]   I. Vamza, F. Diaz, P. Resnais, A. Radziņa, and D. Blumberga, "Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia," *Environmental and Climate Technologies*, vol. 25, no. 1, pp. 58–70, 2021, doi: 10.2478/rtuect-2021-0005.

[38]   R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel, "Cross laminated timber (CLT): overview and development," *European Journal of Wood and Wood Products*, vol. 74, no. 3, pp. 331–351, 2016, doi: 10.1007/s00107-015-0999-5.

[39]   A. Hafner, S. Ott, and S. Winter, "Recycling and End-of-Life Scenarios for Timber Structures," in *Materials and Joints in Timber Structures*, S. Aicher, H.-W. Reinhardt, and H. Garrecht, Eds., Dordrecht: Springer Netherlands, 2014, pp. 89–98. doi: 10.1007/978-94-007-7811-5_8.

[40]   J. Ranganathan, L. Corbier, P. Bhatia, S. Schmitz, P. Gage, and K. Oren, "The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard," 2004, *World Resources Institute and World Business Council for Sustainable Development*.

[41]   S. Horn, K. M. Mölsä, J. Sorvari, H. Tuovila, and P. Heikkilä, "Environmental sustainability assessment of a polyester T-shirt – Comparison of circularity strategies," *Science of The Total Environment*, vol. 884, p. 163821, 2023, doi: 10.1016/j.scitotenv.2023.163821.

[42]   European Commission., "EU Strategy for Sustainable and Circular Textiles." [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0141

[43]   C. Stone, F. M. Windsor, M. Munday, and I. Durance, "Natural or synthetic – how global trends in textile usage threaten freshwater environments," *Science of The Total Environment*, vol. 718, p. 134689, 2020, doi: 10.1016/j.scitotenv.2019.134689.

[44] J. Sohn, K. S. Nielsen, M. Birkved, T. Joanes, and W. Gwozdz, "The environmental impacts of clothing: Evidence from United States and three European countries," *Sustainable Production and Consumption*, vol. 27, pp. 2153–2164, 2021, doi: 10.1016/j.spc.2021.05.013.

[45] P. Jana, "Challenges in the Traditional Fashion and Textile Supply Chain," in *Lean Supply Chain Management in Fashion and Textile Industry*, in Textile Science and Clothing Technology. , Springer, Singapore, 2022, pp. 31–45.

[46] T. Karthik and D. Gopalakrishnan, "Environmental Analysis of Textile Value Chain: An Overview," in *Roadmap to Sustainable Textiles and Clothing*, in Textile Science and Clothing Technology. , Springer, Singapore, 2014, pp. 153–188.

[47] C. Palacios-Mateo, Y. Van Der Meer, and G. Seide, "Analysis of the polyester clothing value chain to identify key intervention points for sustainability," *Environmental Sciences Europe*, vol. 33, no. 1, p. 2, 2021, doi: 10.1186/s12302-020-00447-x.

[48] M. Kahoush and N. Kadi, "Towards sustainable textile sector: Fractionation and separation of cotton/ polyester fibers from blended textile waste," *Sustainable Materials and Technologies*, vol. 34, p. e00513, 2022, doi: 10.1016/j.susmat.2022.e00513.

[49] S. Wang and S. Salmon, "Progress toward Circularity of Polyester and Cotton Textiles," *Sustainable Chemistry*, vol. 3, no. 3, pp. 376–403, 2022, doi: 10.3390/suschem3030024.

[50] V. Wagner, M. Keil, C. Lang-Koetz, and T. Viere, "Screening life cycle assessment of medical workwear and potential mitigation scenarios," *Sustainable Production and Consumption*, vol. 40, pp. 602–612, 2023, doi: 10.1016/j.spc.2023.07.026.

[51] A. Gonçalves and C. Silva, "Looking for Sustainability Scoring in Apparel: A Review on Environmental Footprint, Social Impacts and Transparency," *Energies*, vol. 14, no. 11, p. 3032, May 2021, doi: 10.3390/en14113032.

[52] P. Munasinghe, A. Druckman, and D. G. K. Dissanayake, "A systematic review of the life cycle inventory of clothing," *Journal of Cleaner Production*, vol. 320, p. 128852, 2021, doi: 10.1016/j.jclepro.2021.128852.

[53] N. M. van der Velden, M. K. Patel, and J. G. Vogtländer, "LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane," *The International Journal of Life Cycle Assessment*, vol. 19, no. 2, pp. 331–356, Feb. 2014, doi: 10.1007/s11367-013-0626-9.

[54] S. Zhang, C. Xu, R. Xie, H. Yu, M. Sun, and F. Li, "Environmental assessment of fabric wet processing from gate-to-gate perspective: Comparative study of weaving and materials," *Science of The Total Environment*, vol. 857, p. 159495, 2023, doi: 10.1016/j.scitotenv.2022.159495.

[55] G. Sandin and G. M. Peters, "Environmental impact of textile reuse and recycling – A review," *Journal of Cleaner Production*, vol. 184, pp. 353–365, 2018, doi: 10.1016/j.jclepro.2018.02.266.

[56] S. Roos, C. Jönsson, S. Posner, R. Arvidsson, and M. Svanström, "An inventory framework for inclusion of textile chemicals in life cycle assessment," *The International Journal of Life Cycle Assessment*, vol. 24, no. 5, pp. 838–847, 2019, doi: 10.1007/s11367-018-1537-6.

[57] Snigdha, M. Hiloidhari, and S. Bandyopadhyay, "Environmental footprints of disposable and reusable personal protective equipment – a product life cycle approach for body coveralls," *Journal of Cleaner Production*, vol. 394, p. 136166, 2023, doi: 10.1016/j.jclepro.2023.136166.

[58] T. Anh Dao Tran, E. Thauvin, F. Ferraz, E. Drean, L. Schacher, and A. Dominique, "Comparative Life Cycle Assessment of Dental Scrubs Made of Polyester/Cotton and 100% Cotton," 2022, pp. 320–327. doi: 10.1007/978-3-031-08842-1_51.

[59]   F. Jia, S. Yin, L. Chen, and X. Chen, "The circular economy in the textile and apparel industry: A systematic literature review," *Journal of Cleaner Production*, vol. 259, p. 120728, Jun. 2020, doi: 10.1016/j.jclepro.2020.120728.

[60]   N. Saccani, G. Bressanelli, and F. Visintin, "Circular supply chain orchestration to overcome Circular Economy challenges: An empirical investigation in the textile and fashion industries," *Sustainable Production and Consumption*, vol. 35, pp. 469–482, 2023, doi: 10.1016/j.spc.2022.11.020.

[61]   A. Zandberga, S. N. Kalnins, and J. Gusca, "Decision-making Algorithm for Waste Recovery Options. Review on Textile Waste Derived Products," *Environmental and Climate Technologies*, vol. 27, no. 1, pp. 137–149, 2023, doi: 10.2478/rtuect-2023-0011.

[62]   N. R. Chowdhury, S. K. Paul, T. Sarker, and Y. Shi, "Implementing smart waste management system for a sustainable circular economy in the textile industry," *International Journal of Production Economics*, vol. 262, p. 108876, 2023, doi: 10.1016/j.ijpe.2023.108876.

[63]   S. Patwary, "Clothing and Textile Sustainability: Current State of Environmental Challenges and the Ways Forward," *Textile & leather review*, vol. 3, no. 3, pp. 158–173, 2020, doi: 10.31881/TLR.2020.16.

[64]   S. Imran *et al.*, "Assessing the potential of GHG emissions for the textile sector: A baseline study," *Heliyon*, vol. 9, no. 11, p. e22404, 2023, doi: 10.1016/j.heliyon.2023.e22404.

[65]   European Environment Agency, "Textiles and the environment: the role of design in Europe's circular economy. 2022." Accessed: Jan. 16, 2023. [Online]. Available: https://www.eea.europa.eu/publications/textiles-and-the-environment-the

[66]   A. Köhler *et al.*, "Circular economy perspectives in the EU Textile sector," Publications Office of the European Union, Luxembourg, 2021. doi: 10.2760/858144.

[67]   S. Manshoven, "Textiles and the environment in a circular economy." Accessed: Jan. 24, 2023. [Online]. Available: https://ecodesign-centres.org/wp-content/uploads/2020/03/ETC_report_textiles-and-the-enviroment-in-a-circular-economy.pdf

[68]   T. Cooper and S. Claxton, "Garment failure causes and solutions: Slowing the cycles for circular fashion," *Journal of Cleaner Production*, vol. 351, p. 131394, Jun. 2022, doi: 10.1016/j.jclepro.2022.131394.

[69]   N. Šajn, "Textiles and the environment." Accessed: Nov. 16, 2022. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729405/EPRS_BRI(2022)729405_EN.pdf

[70]   I. M. Brieger, J.-P. Jarmer, and M. Muschkiet, "Coping with challenges of textile collection through an innovative framework towards a sustainable textile Circular Economy," University of Limerick, 2021. doi: 10.31880/10344/10167.

[71]   E. Karell and K. Niinimäki, "Addressing the Dialogue between Design, Sorting and Recycling in a Circular Economy," *The Design Journal*, vol. 22, no. sup1, pp. 997–1013, 2019, doi: 10.1080/14606925.2019.1595413.

[72]   E. McCauley and I. Jestratijevic, "Exploring the Business Case for Textile-to-Textile Recycling Using Post-Consumer Waste in the US: Challenges and Opportunities," *Sustainability*, vol. 15, no. 2, p. 1473, 2023, doi: 10.3390/su15021473.

[73]   F. Binet, I. Coste-Manière, C. Decombes, Y. Grasselli, D. Ouedermi, and M. Ramchandani, "Fast Fashion and Sustainable Consumption," in *Fast Fashion, Fashion Brands and Sustainable*

Consumption, S. S. Muthu, Ed., in Textile Science and Clothing Technology. , Singapore: Springer Singapore, 2019, pp. 19–35. doi: 10.1007/978-981-13-1268-7_2.

[74] B. Zhang, Y. Zhang, and P. Zhou, "Consumer Attitude towards Sustainability of Fast Fashion Products in the UK," *Sustainability*, vol. 13, no. 4, p. 1646, 2021, doi: 10.3390/su13041646.

[75] M. Valtere, T. Bezrucko, and D. Blumberga, "Analysis of Textile Circularity Potential," *Environmental and Climate Technologies*, vol. 27, no. 1, pp. 220–232, 2023, doi: 10.2478/rtuect-2023-0017.

[76] T. Heimann, "Bioeconomy and SDGs: Does the Bioeconomy Support the Achievement of the SDGs?," *Earth's Future*, vol. 7, no. 1, pp. 43–57, Jan. 2019, doi: 10.1029/2018EF001014.

[77] I. Muizniece, A. Kubule, and D. Blumberga, "Towards understanding the transdisciplinary approach of the bioeconomy nexus," *Energy Procedia*, vol. 147, pp. 175–180, Aug. 2018, doi: 10.1016/j.egypro.2018.07.052.

[78] UNEP, "Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication," 2011, *UNEP*.

[79] European Commission, "A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, COM (2011) 112 final," 2011, *Brussels: EC*.

[80] J. Bloomfield and F. Steward, "The Politics of the Green New Deal," *The Political Quarterly*, vol. 91, no. 4, pp. 770–779, Oct. 2020, doi: 10.1111/1467-923X.12917.

[81] B.-O. Linnér and V. Wibeck, "Conceptualising variations in societal transformations towards sustainability," *Environmental Science & Policy*, vol. 106, pp. 221–227, Apr. 2020, doi: 10.1016/j.envsci.2020.01.007.

[82] A. Ruse and J. Pubule, "The Boundaries of Scientific Innovation in the EU Green Deal Context," *Environmental and Climate Technologies*, vol. 26, no. 1, pp. 115–128, Jan. 2022, doi: 10.2478/rtuect-2022-0010.

[83] Drycleaning Institute of Australia Ltd, "International fair claims guide for consumer textiles products." Accessed: Jan. 25, 2023. [Online]. Available: https://irp-cdn.multiscreensite.com/670b4da8678441db9ca09d24ced7de7c/files

[84] S. Pesnel and J. Payet, "Product Environmental Footprint Category Rules (PEFCR) T-shirts." Accessed: Jan. 25, 2023. [Online]. Available: https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_tshirt.pdf

[85] V. Botta and I. Cabral, "Durable, repairable and mainstream. How ecodesign can make our textiles circular.".

[86] S. Manshoven, "Plastic in textiles: potentials for circularity and reduced environmental and climate impact." Accessed: Jan. 26, 2023. [Online]. Available: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts

[87] European Commission., "Data on the EU textile ecosystem and its competitiveness: Final report." Accessed: Feb. 22, 2023. [Online]. Available: https://data.europa.eu/doi/10.2873/23948

[88] M. Valtere *et al.*, "The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran," *Environmental and Climate Technologies*, vol. 26, no. 1, pp. 658–669, Jan. 2022, doi: 10.2478/rtuect-2022-0050.

[89] P. Li, H. Qian, J. Wu, and J. Chen, "Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights," *Environmental Monitoring and Assessment*, vol. 185, no. 3, pp. 2453–2461, Mar. 2013, doi: 10.1007/s10661-012-2723-9.

[90] G. Viksne, I. Vamža, V. Terjanika, T. Bezrucko, J. Pubule, and D. Blumberga, "CO 2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios," *Environmental and Climate Technologies*, vol. 26, no. 1, pp. 1158–1168, Jan. 2022, doi: 10.2478/rtuect-2022-0087.

[91] K. Gruduls, "Characteristics of wood chips from logging residues and quality influencing factors," *Research for Rural Development*, vol. 2, pp. 49–54, 2013.

[92] L. Tellnes, C. Ganne-Chedeville, A. Dias, F. Dolezal, C. Hill, and E. Zea Escamilla, "Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: a review study for construction materials based on forest products," *iForest - Biogeosciences and Forestry*, vol. 10, no. 5, pp. 815–823, Oct. 2017, doi: 10.3832/ifor2386-010.

[93] FAO, ITTO, and UN, "Forest product conversion factors," 2020, *FAO, Rome*.

[94] Dieffenbacher, "Fibre Insulation Board lines." Accessed: Apr. 20, 2022. [Online]. Available: https://www.environmental-expert.com/products/fibre-insulation-board-lines-190613

[95] J. Pubule, D. Blumberga, F. Romagnoli, and M. Rochas, "Analysis of the environmental impact assessment of power energy projects in Latvia," *Management of Environmental Quality: An International Journal*, vol. 23, no. 2, pp. 190–203, Feb. 2012, doi: 10.1108/14777831211204930.

[96] BRE Ltd, *BRE Global Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012+A1:2013*. Watford: BRE Group, 2014.

[97] A. Balkan Green Energy News, "5 MWe biomass cogeneration plant officially opened in the city of Slatina." [Online]. Available: https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/

[98] U.S. Department of Energy, "Combined Heat and Power Technology Fact Sheet Series: Gas turbines," 2019, *DoE, Washington*.

[99] Danish Energy Agency, "Technology Data for Energy Plants for Electricity and District Heating generation.," 2019, *DEA, Copenhagen*.

[100] T. Abbas, M. Issa, and A. Ilinca, "Biomass Cogeneration Technologies: A Review," *Journal of Sustainable Bioenergy Systems*, vol. 10, no. 01, pp. 1–15, 2020, doi: 10.4236/jsbs.2020.101001.

[101] I. Tsiropoulos, D. Tarvydas, and A. Zucker, "Cost development of low carbon energy technologies," 2018, *Publication Office of European Union*.

[102] D. Zalamane, "Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā ar dabasgāzi (The price of wood chips is rising, heating with wood chips is 5 times cheaper than with natural gas.)." Accessed: Apr. 20, 2022. [Online]. Available: https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka-.a155970/

[103] "'Latvijas gaze' brīdina par dabasgāzes biržas cenas trīskāršu pieaugumu aprīlī ('Latvian gas' warns of a threefold increase in natural gas exchange prices in April)." Accessed: Apr. 20, 2022. [Online]. Available: https://www.lsm.lv/raksts/zinas/ekonomika/latvijas-gaze-bridina-par-dabasgazes-birzas-cenas-triskarsu-pieaugumu-aprili.a446800/

[104] K. Darrow, "Catalogue of CHP technologies," 2017, *EPA, Boston*.

[105] Cabinet of Ministers, "Methodology for calculating greenhouse gas emissions," 2018, *Latvijas Vestnesis*.

[106] A. Ishizaka and P. Nemery, *Multi-criteria Decision Analysis: Methods and Software*. USA: Wiley, 2013.

[107] "2006 Environmental Management - Life Cycle Assessment - Principles and Framework," 2006, *ISO, Geneva, Switzerland*.

[108] E. L. Schmidt, M. Riggio, A. R. Barbosa, and I. Mugabo, "Environmental response of a CLT floor panel: Lessons for moisture management and monitoring of mass timber buildings," *Building and Environment*, vol. 148, pp. 609–622, 2019, doi: 10.1016/j.buildenv.2018.11.038.

[109] M. Wieruszewski and B. Mazela, "Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood," *Drvna industrija*, vol. 68, no. 4, pp. 359–367, 2017, doi: 10.5552/drind.2017.1728.

[110] Ecoinvent, "waste wood, untreated."

[111] Ecoinvent, "sawdust, loose, wet, measured as dry mass."

[112] Ecoinvent

[113] Ecoinvent, "cross laminated timber production."

[114] K. Dolge and D. Blumberga, "What are the Linkages between Climate and Economy? Bibliometric Analysis," *Environmental and Climate Technologies*, vol. 26, no. 1, pp. 616–629, 2022, doi: 10.2478/rtuect-2022-0047.

[115] M. El Mohadab, B. Bouikhalene, and S. Safi, "Bibliometric method for mapping the state of the art of scientific production in Covid-19," *Chaos, Solitons & Fractals*, vol. 139, p. 110052, 2020, doi: 10.1016/j.chaos.2020.110052.

[116] "Introduction to the Database," 2024.

[117] J. Duggan, "An Introduction to System Dynamics," in *System Dynamics Modeling with R*, in Lecture Notes in Social Networks. , Springer, Cham, 2016, pp. 1–24.

[118] Y. A. Alamerew and D. Brissaud, "Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries," *Journal of Cleaner Production*, vol. 254, p. 120025, 2020, doi: 10.1016/j.jclepro.2020.120025.

[119] Y. Kazancoglu, E. Ekinci, S. K. Mangla, M. D. Sezer, and Y. Kayikci, "Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics," *Business Strategy and the Environment*, vol. 30, no. 1, pp. 71–91, 2021, doi: 10.1002/bse.2610.

[120] M. A. Franco, "A system dynamics approach to product design and business model strategies for the circular economy," *Journal of Cleaner Production*, vol. 241, p. 118327, 2019, doi: 10.1016/j.jclepro.2019.118327.

[121] T.-C. Kuo, N.-Y. Hsu, R. Wattimena, I.-H. Hong, C.-J. Chao, and J. Herlianto, "Toward a circular economy: A system dynamic model of recycling framework for aseptic paper packaging waste in Indonesia," *Journal of Cleaner Production*, vol. 301, p. 126901, 2021, doi: 10.1016/j.jclepro.2021.126901.

[122] C. Gao, C. Gao, K. Song, and K. Fang, "Pathways towards regional circular economy evaluated using material flow analysis and system dynamics," *Resources, Conservation and Recycling*, vol. 154, p. 104527, 2020, doi: 10.1016/j.resconrec.2019.104527.

[123] S. Lähdesmäki, J. Hanski, and E. Huttunen-Saarivirta, "Insights into Circular Economy Potential of Lithium by System Dynamic Modelling of Material Streams," *Batteries & Supercaps*, vol. 6, no. 12, p. e202300231, 2023, doi: 10.1002/batt.202300231.

[124] D. Guzzo, D. C. A. Pigosso, N. Videira, and J. Mascarenhas, "A system dynamics-based framework for examining Circular Economy transitions," *Journal of Cleaner Production*, vol. 333, p. 129933, 2022, doi: 10.1016/j.jclepro.2021.129933.

[125] L. Schoenenberger, A. Schmid, R. Tanase, M. Beck, and M. Schwaninger, "Structural Analysis of System Dynamics Models," *Simulation Modelling Practice and Theory*, vol. 110, p. 102333, 2021, doi: 10.1016/j.simpat.2021.102333.

[126] European Commission., "A new Circular Economy Action Plan." [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[127] G. Braun, C. Som, M. Schmutz, and R. Hischier, "Environmental Consequences of Closing the Textile Loop—Life Cycle Assessment of a Circular Polyester Jacket," *Applied Sciences*, vol. 11, no. 7, p. 2964, 2021, doi: 10.3390/app11072964.

[128] S. Madhav, A. Ahamad, P. Singh, and P. K. Mishra, "A review of textile industry: Wet processing, environmental impacts, and effluent treatment methods," *Environmental Quality Management*, vol. 27, no. 3, pp. 31–41, 2018, doi: 10.1002/tqem.21538.

[129] S. Hann, C. Sherrington, O. Jamieson, M. Hickman, P. Kershaw, and A. Bapasola, "Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products," 2018.

[130] T. Semba, Y. Sakai, M. Ishikawa, and A. Inaba, "Greenhouse Gas Emission Reductions by Reusing and Recycling Used Clothing in Japan," *Sustainability*, vol. 12, no. 19, p. 8214, 2020, doi: 10.3390/su12198214.

[131] X. Huang *et al.*, "Industrialization of open- and closed-loop waste textile recycling towards sustainability: A review," *Journal of Cleaner Production*, vol. 436, p. 140676, 2024, doi: 10.1016/j.jclepro.2024.140676.

[132] R. Hornbuckle, K. Goldsworthy, and L. Knight, "A Systemic Material Innovation Study of the Current State and Future Possibilities for Circular Polyester," *Sustainability*, vol. 15, no. 12, p. 9843, 2023, doi: 10.3390/su15129843.

[133] Eurostat, "Population change - Demographic balance and crude rates at national level."

[134] Eurostat, "Short-term update of the projected population (2022-2032)."

[135] United States Environmental Protection Agency, "Nondurable Goods: Product-Specific Data." Accessed: Nov. 15, 2022. [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/nondurable-goods-product-specific-data#ClothingandFootwear

[136] S. Egerer, R. V. Cotera, L. Celliers, and M. M. Costa, "A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture," *Agricultural Systems*, vol. 189, p. 103052, 2021, doi: 10.1016/j.agsy.2021.103052.

[137] J. Duggan, "Modeling Limits to Growth," in *System Dynamics Modeling with R*, in Lecture Notes in Social Networks. , Cham: Springer International Publishing, 2016, pp. 49–71. doi: 10.1007/978-3-319-34043-2_3.

[138] I. Pakere, M. Kacare, A. Grāvelsiņš, R. Freimanis, and A. Blumberga, "Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia," *Smart Energy*, vol. 7, p. 100081, 2022, doi: 10.1016/J.SEGY.2022.100081.

[139] A. Blumberga, G. Bazbauers, P. I. Davidsen, D. Blumberga, A. Gravelsins, and T. Prodanuks, "System dynamics model of a biotechonomy," *Journal of Cleaner Production*, vol. 172, pp. 4018–4032, 2018, doi: 10.1016/J.JCLEPRO.2017.03.132.

[140] M. Schmidt, "The Sankey Diagram in Energy and Material Flow Management: Part II: Methodology and Current Applications," *Journal of Industrial Ecology*, vol. 12, no. 2, pp. 173–185, 2008, doi: 10.1111/j.1530-9290.2008.00015.x.

[141] S. A. Gray, S. Gray, L. J. Cox, and S. Henly-Shepard, "Mental Modeler: A Fuzzy-Logic Cognitive Mapping Modeling Tool for Adaptive Environmental Management," in *2013 46th Hawaii International Conference on System Sciences*, IEEE, Jan. 2013, pp. 965–973. doi: 10.1109/HICSS.2013.399.

[142] S. Gray and E. Zanre, "Gray S. Fuzzy Cognitive Maps as representations of mental models and group beliefs: theoretical and technical issues. Fuzzy Cognitive maps for Applied Sciences and Engineering - From fundamentals to extensions and learning algorithms.," *Springer Publishing*, 2013.

[143] S. Gray, A. Chan, D. Clark, and R. Jordan, "Modeling the integration of stakeholder knowledge in social–ecological decision-making: Benefits and limitations to knowledge diversity," *Ecological Modelling*, vol. 229, pp. 88–96, Mar. 2012, doi: 10.1016/j.ecolmodel.2011.09.011.

[144] S. R. J. Gray *et al.*, "Are coastal managers detecting the problem? Assessing stakeholder perception of climate vulnerability using Fuzzy Cognitive Mapping," *Ocean & Coastal Management*, vol. 94, pp. 74–89, Jun. 2014, doi: 10.1016/j.ocecoaman.2013.11.008.

[145] B. Kosko, "Fuzzy cognitive maps," *International Journal of Man-Machine Studies*, vol. 24, no. 1, pp. 65–75, Jan. 1986, doi: 10.1016/S0020-7373(86)80040-2.

[146] Gore & Associates W. L, "Life Cycle Assessment of a GORE branded waterproof, windproof and breathable jacket." Accessed: Jan. 24, 2023. [Online]. Available: https://www.gore-tex.com/sites/default/files/assets/Gore_LCA_summary_report.pdf

[147] S. Nolimal, "Life Cycle Assessment of Four Different Sweaters," DePaul Discoveries. Accessed: Jan. 24, 2023. [Online]. Available: https://via.library.depaul.edu/depaul-disc/vol7/iss1/9

[148] LAPCO FR, "FR Clothing Wash Expectancy – Useful Life." Accessed: Jan. 26, 2023. [Online]. Available: https://www.lapco.com/blogs/fr-education-guides/how-many-times-can-you-wash-fire-retardant-clothing

[149] Collective Data, "Why Bulletproof Vests Expire?" Accessed: Jan. 26, 2023. [Online]. Available: https://collectivedata.com/articles/why-bulletproof-vests-expire/

[150] Economy Tent International, "Everything You Need to Know about Commercial Tents." Accessed: Jan. 26, 2023. [Online]. Available: https://economytent.com/everything-you-need-to-know-about-commercial-tents/

[151] Outdoorline, "Down or synthetic insulation?" Accessed: Jan. 26, 2023. [Online]. Available: https://www.outdoorline.sk/en/content/down-or-synthetic-insulation

[152] Research and Markets, "$605.4 Billion Worldwide Apparel Industry Report to 2031 – Identify Growth Segments for Investment."

[153] Research and Markets, "Global Home Textile Market Report 2022: Expected Value of $145.05 Billion by 2026." Accessed: Jan. 27, 2022. [Online]. Available: https://www.globenewswire.com/en/news-release/2022/07/05/2473738/28124/en/Global-Home-Textile-Market-Report-2022-Expected-Value-of-145-05-Billion-by-2026.html

[154] The Business Research Company, "Technical Textiles Global Market Report 2022." Accessed: Jan. 27, 2023. [Online]. Available: https://www.reportlinker.com/p06313445/Technical-Textiles-Global-Market-Report.html

[155] EURATAX, "Facts and key figures 2022 of the European textile and clothing industry." Accessed: Jan. 30, 2023. [Online]. Available: https://euratex.eu/wp-content/uploads/EURATEX_FactsKey_Figures_2022rev-1.pdf

[156] S. Yasin, "A case study of life cycle inventory of cotton curtain." Accessed: Jan. 30, 2023. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01984356

[157] J. Sim and V. Prabhu, "The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States," *Journal of Cleaner Production*, vol. 170, pp. 1231–1243, Jan. 2018, doi: 10.1016/j.jclepro.2017.09.203.

[158] A. C. for L. C. Assessment, *ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017*. Washington: ACLCA, 2019.

[159] European Commission Joint Research Centre Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) Handbook. General guide for Life Cycle Assessment. Detailed guidance*. Luxembourg: Publications Office of the European Union, 2010.

[160] "PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.," 2011.

[161] O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, "Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method," *Energies*, vol. 15, no. 7, p. 2708, 2022, doi: 10.3390/en15072708.

[162] European Commission. Joint Research Centre., "Best available techniques (BAT) reference document for the textiles industry: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control)," LU: Publications Office. [Online]. Available: https://data.europa.eu/doi/10.2760/355887

[163] Y. Zhang *et al.*, "Improved design for textile production process based on life cycle assessment," *Clean Technologies and Environmental Policy*, vol. 20, no. 6, pp. 1355–1365, 2018, doi: 10.1007/s10098-018-1572-9.

[164] B. Sara and M. Tarantini, "Life Cycle Assessment of cotton/polyester fabric in B05 company," 2003.

[165] K. Subramanian, S. S. Chopra, E. Cakin, X. Li, and C. S. K. Lin, "Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup," *Resources, Conservation and Recycling*, vol. 161, p. 104989, 2020, doi: 10.1016/j.resconrec.2020.104989.

[166] M. Zhao *et al.*, "Virtual carbon and water flows embodied in global fashion trade - a case study of denim products," *Journal of Cleaner Production*, vol. 303, p. 127080, 2021, doi: 10.1016/j.jclepro.2021.127080.

[167] S. Msahli and F. Debbabi, Eds., *Advances in Applied Research on Textile and Materials - IX*, vol. 17. in Springer Proceedings in Materials, vol. 17. Cham: Springer International Publishing, 2022. doi: 10.1007/978-3-031-08842-1.

[168] J. Jewell, C. Koffler, and S. Murphy, "LCA Update of Cotton Fiber and Fabric Life Cycle Inventory," Cotton Incorporated, 2017.

[169] X. Wang, J. Jiang, and W. Gao, "Reviewing textile wastewater produced by industries: characteristics, environmental impacts, and treatment strategies," *Water Science and Technology*, vol. 85, no. 7, pp. 2076–2096, 2022, doi: 10.2166/wst.2022.088.

[170] E. Boschmeier, W. Ipsmiller, and A. Bartl, "Market assessment to improve fibre recycling within the EU textile sector," *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 42, no. 2, pp. 135–145, 2024, doi: 10.1177/0734242X231178222.

[171] D'Amato, D., Droste, N., Allen, B., et al. (2020). Green, circular, bio economy: A comparative analysis of sustainability avenues. Journal of Cleaner Production, 259, 120904.

[172] Bugge, M. M., Hansen, T., & Klitkou, A. (2016). What is the bioeconomy? A review of the literature. Sustainability, 8(7), 691.

[173] Gustavsson, J., Cederberg, C., Sonesson, U., et al. (2011). Global food losses and food waste. FAO Report.

[174] Food and Agriculture Organization (FAO). (2019). The state of food and agriculture: Moving forward on food loss and waste reduction. Rome: FAO.

[175] OECD. (2018). Meeting Policy Challenges for a Sustainable Bioeconomy. OECD Publishing.

[176] Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., & Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development, 15, 3–34.

[177] https://oeil.secure.europarl.europa.eu/oeil/en/procedure-file?reference=2020/2077(INI)

[178] European Parliament. Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast); European Union: Brussels, Belgium, 2023.

[179] Energy Efficiency Directive. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targetsdirective-and-rules/energy-efficiency-directive_en (accessed on 17 December 2024).

[180] Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast) (Text with EEA Relevance); European Union: Brussels, Belgium, 2024.

[181] Wohlfarth, K.; Eichhammer, W.; Schlomann, B.; Mielicke, U. Learning networks as an enabler for informed decisions to target energy-efficiency potentials in companies. J. Clean. Prod. 2017, 163, 118–127.

[182] European Commission. European Commission REPowerEU: Energy Savings and Energy Efficiency. Available online: https://ec.europa.eu/commission/presscorner/detail/en/fs_22_3137 (accessed on 6 December 2024).

[183] Collombet, R.; Peillon, R.H. Energy Performance of Buildings Directive: Implementation Guide. Available online: https:// efficientbuildings.eu/wp-content/uploads/2024/10/Efficient-Buildings-Europe-Implementation-Guide-2024_online-1.pdf (accessed on 9 January 2025).

[184] Kubule, A.; Loˇcmelis, K.; Blumberga, D. Analysis of the results of national energy audit program in Latvia. Energy 2020, 202, 117679.

PUBLIKĀCIJU KOPA

1. Publikācija:
   Valtere, M., Bezručko, T., Blumberga, D. Analysis of Textile Circularity Potential. Environmental and Climate Technologies, 2023, Vol. 27, No. 1, 220.-232.lpp. e-ISSN 2255-8837. Pieejams: doi:10.2478/rtuect-2023-0017

2. Publikācija:
   Vīksne, G., Vamža, I., Terjaņika, V., Bezručko, T., Pubule, J., Blumberga, D. CO2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios. Environmental and Climate Technologies, 2022, Vol. 26, No. 1, 1158.-1168.lpp. e-ISSN 2255-8837. Pieejams: doi:10.2478/rtuect-2022-0087

3. Publikācija:
   Vasuks, P., Vamža, I., Valtere, M., Bezručko, T., Blumberga, D. Recycled Cross-Laminated Timber as a Low Environmental Impact Alternative to Virgin Material: Latvia Case Study. Case Studies in Construction Materials, 2025, Vol. 22, Article number e04094. e-ISSN 2214-5095. Available from: doi:10.1016/j.cscm.2024.e04094

4. Publikācija:
   Valtere, M., Bezručko, T., Poberznik, M., Vamža, I., Blumberga, D. Uncertainty of Life Cycle Assessment Studies for Blended Textiles. Environmental and Climate Technologies, 2024, Vol. 28, No. 1, 794.-811.lpp. ISSN 1691-5208. e-ISSN 2255-8837. Pieejams: doi:10.2478/rtuect-2024-0061

5. Publikācija:
   Liberova, V., Brēmane, I., Lauka, D., Laktuka, K., Bezručko, T., Zvirbule, K., Bezručko, A., Blumberga, D. Unleashing Energy Potential: Insights of Energy Audit Practices. Energies, 2025, Vol. 18, No. 3, Article number 522. e-ISSN 1996-1073. Pieejams: doi:10.3390/en18030522

6. Publikācija:
   Valtere, M., Bezručko, T., Lauka, D., Blumberga, A., Blumberga, D. What Drives the Circular Economy? Textile Sorting or Consumption Reduction. Circular Economy and Sustainability, 2025, Vol. 5, 2725.-2749.lpp. ISSN 2730-597X. Pieejams: doi:10.1007/s43615-025-00584-6

7. Publikācija:
   Bezručko, T., Lauka, D., Laktuka, K., Sniega, L., Vamža, I., Dzalbs, A., Terjaņika, V., Blumberga, D. Bioeconomy towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps. Environmental and Climate Technologies, 2022, Vol. 26, No. 1, 684.-696.lpp. e-ISSN 2255-8837. Pieejams: doi:10.2478/rtuect-2022-0052

8. Publikācija:
   Valtere, M., Bezručko, T., Liberova, V., Blumberga, D. Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development. Environmental and Climate Technologies, 2025, Vol. 29, No. 1, 323.-343.lpp. ISSN 1691-5208. e-ISSN 2255-8837. Pieejams: doi:10.2478/rtuect-2025-0023

Analysis of Textile Circularity Potential

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Abstract – **Global annual textile consumption has doubled in the last two decades and is expected to keep increasing. Since the textile system operates primarily in a linear way, it is highly polluting and creates a lot of waste. But nevertheless, it has a high potential for circularity since most textile products can be recycled or reused. Today most of the waste ends up in landfills, and less than 1 % is recycled back into textiles. This study aims to gather information and evaluate which textile product group has the highest potential for circular economy growth. It covers three main textile product streams: fashion, home, and technical textiles. The groups were compared using fifteen criteria: environmental impact, washes, landfilled waste, recycled waste, origin of fabric, projected lifetime, market demand, production volume, international trade, labour productivity, value added, energy efficiency of production technologies, innovation capacity, employment, and enterprises. Input values have been found for each sustainability indicator by using and mathematically transforming data from the scientific literature. The evaluation method used in this study was multi-criteria decision analysis. The results indicated that the fashion textile group has the most significant potential for circular economy development, mainly because it is the largest textile product stream, and the development of a circular economy could be cost-effective.**

Keywords – **Apparel; circular economy; home textiles; multi-criteria decision analysis (MCDA); technical textiles; TOPSIS.**

1. INTRODUCTION

The population growth, improvement of living standards, and decreased lifetime of textile products have led to doubled global annual consumption and production in the last two decades [1]. That has a negative impact on the environment since the textile industry is highly polluting, resource intensive, and creates a lot of waste. In the whole life cycle, around 87 % of input fibres end up in landfills, and less than 1 % is recycled back into textiles. The lost opportunity was valued at more than EUR 93 billion in 2017 [2].

The textile sector plays an important role in the transition to climate neutrality, as 10 % of global carbon emissions come from textile production [3]. The textile system is currently operating primarily in a linear way [2], but it has great potential for circularity because most textile products could potentially be recycled or reused. For example, if a circular economy were implemented in the fashion textiles value chain, around 95 % of fashion textiles could be returned back into the supply chain – more than 60 % of all clothes could be reused, 35 % recycled, and just 5 % would be discarded [4].

The transition from a linear to a circular economy is a necessity. Our society consumes more than the Earth can produce. That is shown by Earth Overshoot Day, which indicates the

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date each year when all natural resources that could renew in that year are exhausted. In 2022 it was July 28 [5]. The core of the circular economy is to prevent waste generation in all systems by extending the product's life cycle, repairing, reusing, and recycling [6]. The textile product group has been set by Europe Union (EU) as one of the seven key product value chains that will be prioritized in the transition to the circular economy [7]. Also, the circular economy development in the textile sector is in line with at least six of the seventeen United Nations Sustainable Development Goals (Goal 3;6;8;9;12;14) [8].

This study looks at three main textile product streams: fashion, home, and technical textiles. Fashion textiles include clothing and footwear, but in this study, the focus is on clothing. This category is the largest, accounting for approximately 60 % of the total textile volume, and is expected to remain so [2]. Home textiles include all textile products used for internal spaces and furnishings. This study focuses on bed, toilet, and kitchen linens such as sheets, towels, and tablecloths. Home textile consumption has been relatively steady over time. In 2020, it slightly increased, but the consumption of clothing decreased [9]. That can be explained by the COVID-19 pandemic and lockdown. Technical textiles include fabrics that main criteria are functionality, not ascetics. These textiles are applied in many industries like construction, automobile, aerospace, sports, defense, and agriculture. Because of its wide usage, it is fast growing textile category [10].

Multi-criteria decision analysis (MCDA) is a common method for solving decision-making problems. It is suitable for any field that can define a problem, criteria, and alternatives that need to be compared [11]. MCDA is also used in research in the textile sector. Eda Acar *et al*. used MCDA in their study to evaluate a textile company's environmental sustainability performance [12]. They used 25 criteria, and the alternatives were the company's yearly performance in a period from 2008 to 2012. The indicator values were calculated based on data from each year divided by the number of garments produced that year to get a value per unit. Because of this approach, the developed framework also could be used for other textile companies' sustainability evaluation. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was the MCDA method used in the reviewed research. It will also be the method used in this study.

There are many studies about sustainability and the possibilities of transitioning to a circular economy in the textile sector [13]. The authors cover topics such as consumer behaviour [14], textile recycling and reuse [4], environmental impact [15], waste generation in the sector [16], life cycle assessment of a specific textile product [17], eco-labels [18], and so on. Most of these studies focus on the entire textile sector or only on fashion textiles. However, as far as we know, there has been no compilation of information on each textile group separately, and the development opportunities of the circular economy in all these segments have not been analysed. Therefore, this study aims to gather information from the scientific literature and evaluate which textile product group has the highest potential for circular economy growth based on economic, environmental, social, and technical criteria.

2. METHODOLOGY

The methodology was chosen based on the reviewed papers [11], [12] and the aim of this study. Two methods were selected to gather data and evaluate the textile product streams – literature review and MCDA. For this study, the operation algorithm can be defined in the following four steps:
1. Compilation of information on each group of textile products from the available literature;
2. Selection of criteria based on the analysis of the literature;

3. Performing MCDA analysis based on selected criteria and data;
4. Policy improvement recommendations based on the obtained results.

2.1. Literature review

Primarily scientific literature databases were used in the literature review. After reviewing the literature, an understanding of what information is available about textile product groups was formed. Then from reviewed literature, data were collected and mathematically transformed for further analyses. Non-scientific sources and assumptions were used in cases when data were not available.

2.2. Selection of criteria

The next stage of research was criteria selection. Criteria were selected based on the relevance to the aim of the research and available data. To evaluate the possibility of circular economy development, criteria represent four categories- environmental, economic, social, and technical aspects. The chosen fifteen criteria are shown in Table 1. Criteria also can be used to measure sustainable development since they represent three sustainability pillars: the economy, society, and the environment [19]. The technical aspect is included to make the analysis more diverse and relate more to circular economy development.

TABLE 1. CRITERIA FOR MULTI-CRITERIA DECISION ANALYSIS

Criteria category	Criteria	Ideal value
Environmental aspects	Environmental impact – global warming potential of a product, $kgCO_2eq\ kg^{-1}$	+
	Washes – environmental impact of use-phase defined by average washes of a textile product, times	+
	Projected lifetime – average lifetime of the product, years	−
	Landfilled waste – landfilled waste ratio from the total waste amount, %	+
	Recycled waste – recycled waste ratio from the total waste amount, %	−
	Origin of fabric – a ratio of synthetic materials, %	+
Economic aspects	Market demand – global market size assessment, billion EUR	+
	Production volume – a ratio of produced product amount, %	+
	International trade – a ratio of exported product amount, %	+
	Labour productivity – gross value added per person employed, thousand EUR	+
	Value added – share of value added over total manufacturing, %	+
Technical aspects	Energy efficiency of production technologies– a ratio of energy usage in the products production stage from energy usage in a total lifecycle, %	+
	Innovation capacity - number of patents filed between 2015 and 2019, patents	+
Social aspects	Employment – share of persons employed in the sector, %	+
	Enterprises – share of enterprises in the sector, %	+

The ideal value is shown as "+" or "−"; if the ideal value is maximal value, then the criteria are represented with a plus symbol, but if the ideal value is minimal value, then there is the opposite symbol. In this case, since the aim is to find which group has the most opportunity

for circular economy development, rather than which sector already has the highest circularity, the ideal values of the environmental and technical aspects are counterintuitive. For example, a higher environmental impact is defined as the ideal case because if a textile group has a high environmental impact, this indicates that it is unlikely to have taken steps to improve sustainability, such as circular economy measures. Therefore, there are many opportunities for the development of a circular economy in this sector. Recycled waste is another example. The less waste is recycled in a sector, the more it can be recycled, so there is greater potential for developing a circular economy.

2.2.1. Environmental aspects

Environmental impact was determined after Life Cycle Assessment (LCA) studies. There are no LCA studies that examine the entire textile group. Therefore, when evaluating this indicator, the LCA for textile products from each stream was taken. The global warming potential (GWP) of a product was the quantitative measure used in further analysis.

A wash time criterion was introduced to evaluate the use-phase of textiles. About 14 % of the climate change impact of textiles occurs during the use-phase, as significant water and energy consumption happens during the washing and drying of materials [9]. Also, in this life cycle stage pollution from chemicals and microplastics is formed in the marine environment [20]. Thus, this criterion is used to evaluate environmental impact.

The other use phase criterion that was chosen is projected lifetime. Since wash time frequency depends on the textile product, washes indicator cannot fully describe its life span. For example, a T-shirt is washed frequently but has a short lifetime [21], [22], indicating that a high number of washes over the lifetime of a product does not necessarily indicate that the product has a long lifetime. The lifetime depends largely on the user and the quality of the textile [23]. The lifetime of the textile product is an important indicator of environmental impact. The longer the use of the textile product, the smaller the environmental impact. For instance, it is estimated that the environmental impact would be reduced by 20 to 30 % if the lifetime of the garment was nine months longer [24].

To assess end-of-life environmental impacts, two criteria were added: landfilled waste and recycled waste. Textiles are most likely to end up in landfill or incinerated after the use phase [2]. If textiles are sorted, they are mostly recycled or reused. There are available data about textile waste management globally, but the data are not divided into textile streams. Globally around 73 % of garments are landfilled or incinerated post-consumer use [2]. It is meaningful to note that most LCA studies assume that the end-of-life stage for all textile products is the same, but in reality, even if the product is made of the same fibre type, the environmental impact is different [3].

A significant factor in the environmental impact assessment of a textile product is the type of material used [25]. Since this study looks at textile product streams and not at specific products, two main material categories were looked at – synthetic and natural fibres. The synthetic material ratio shows how much non-renewable resources are used in each group.

2.2.2. Economic aspects

Market demand was used to evaluate opportunities for economic growth. The size of the market indicates the profitability of circular economy development. The production criterion was created to further understand the distribution of the textile market. The distribution of total textile production by sector indicates the size of the textile product streams. The greater the production volumes, the greater the possibilities for economic development. No data about the global distribution of production is available, so data about the EU was taken.

Export contributes to economic growth in every country. But since this study looks at the global scale, this indicator was created to reflect international trade in textile systems. Environmental pollution occurs during the distribution stage, but as this criterion is considered from an economic point of view, the higher the share of exported products, the more active international trade is in this product flow.

The value added indicates the economic importance of each textile group. Two criteria were established to assess this – labour productivity and value added. The first criterion shows the gross value added per person employed. The higher the value added per employee, the more efficient the sector. The second criterion shows the share of value added in total production, which indicates the economic importance of each textile stream in the overall manufacturing sector.

2.2.3. Technical aspects

It was decided to evaluate energy efficiency of production technologies to include a technical aspect in this study. Data about textile products from each stream were taken since there is no study about the whole stream. We decided to evaluate technology efficiency in the production stage. Therefore, a ratio of energy use in the products production phase from energy use in a full lifecycle was taken. The bigger percentage of energy use, the more inefficient the production technologies are.

Innovation capacity was examined to assess the technological development of each sector. The textile industry regularly delivers innovations in the form of new materials, uses, solutions, and products. Innovation capacity can be evaluated by patents, designs, trademarks, and business research and development expenditures [26]. In this case, the innovation capacity was determined by a number of patents. More patents mean higher innovation capacity.

2.2.4. Social aspects

The social aspect is an influential part of the transition to a circular economy. Thus, a social aspect was included in this study. The aim was to assess employment in each textile product group. Therefore, employment and enterprises were taken as indicators. Employment points to the current situation, while the number of companies outlines future opportunities. More companies mean more and varied job opportunities in the sector. Moreover, the more enterprises, the more likely it is that new jobs will be created.

2.3. MCDA

As mentioned before, in this study MCDA method, more specifically, TOPSIS, will be used for data analyses. In our case, all data are quantitative, but in this method, also qualitative data can be used [11]. The result is the distance of alternatives to an ideal point. The ideal point in this method is value one, which means that the alternative with the value closest to one is the best [11]. MS Excel was used for TOPSIS calculations. The MCDA has three steps [27]:

1. Define input data – all calculations are based on input data and the chosen alternatives and criteria. Table 1 shows fifteen criteria for this study, and alternatives are the three main textile product streams – fashion, home, and technical textiles.
2. Weights of criteria – different weights are given for criteria to compare their importance. The weights can be defined using the Analytical Hierarchy Process (AHP) and Sensitivity Analysis. Since there are more than seven criteria, the results using AHP would be more inconsistent [11]. That is why sensitivity analysis will be used in

this study. Sensitivity analysis was performed with five unitary variation ratios (0.01; 0.5; 2; 3; 4). The analysis steps are explained in Peiyue Li *et al.* study [28].

The criteria were divided into three groups based on the results of the sensitivity analysis: high, medium, and low sensitivity. The distribution of the criteria across the groups was determined by the average of the difference between the highest and lowest alternatives in terms of their relative proximity to the ideal solution. This average value will be referred to as the sensitivity indicator. If the sensitivity indicator was below 0.1, then its sensitivity was considered low; if it was above 0.2, then it was considered high; and if it was between 0.1 and 0.2 inclusive, then the sensitivity of the criterion was medium. The weight of the high sensitivity criterion was obtained by multiplying the initial weight by 1.5, and the weight of the low sensitivity criterion was obtained by multiplying by 0.5. The weight for a medium sensitivity criterion was calculated by dividing the remaining weight by the number of criteria. The resulting weights were agreed upon with experts in the field to verify that the weight distribution was valid.

3. Calculations of the TOPSIS – five calculation steps were used based on the study of Zlaugotne B. *et al.* [11].

3. RESULTS

3.1. Input data

All obtained input data from the literature review are shown in Table 2. The sources of the values summarized in the table are listed in the following subsections.

TABLE 2. INPUT DATA OF TOPSIS ANALYSIS

Criteria	Alternatives		
	Fashion textile	Home textile	Technical textile
Environmental impact, $kgCO_2eq\ kg^{-1}$	30.42	5.06	81.45
Washes, times	30	68	63
Projected lifetime, years	3.13	4.06	6.13
Landfilled waste, %	70	68	78
Recycled waste, %	13	16	5
Origin of fabric, %	60	70	80
Market demand, billion EUR	511.39	103.31	177.53
Production volume, %	41	14	17
International trade, %	59	2	14
Labour productivity, thousand EUR	22	29	47
Value added, %	1.01	0.28	0.37
Energy efficiency of production technologies, %	54	70	59
Innovation capacity, patents	5001	127	3440
Employment, %	72	16	12
Enterprises, %	75	16	9

3.1.1. Environmental impact

The main source of information for fashion textiles was Gonçalves A. and Silva C. review study [29]. They have gathered the environmental impact of different apparel (see Table 1 from the study). For analysis, we chose a jacket, T-shirt, and four types of sweaters. Only use-phase and end-of-life were considered. The jacket is 0.9 kg, and its GWP is 25.3 kgCO$_2$eq on a functional unit [30]. Therefore, for a 1 kg of jackets, the GWP is 28.1 kgCO$_2$eq. For the T-shirt category, GWP is 5.3 kgCO$_2$eq kg^{-1} t-shirts. We took four types of sweaters – wool, cotton, blend, and acrylic [31]. The average GWP is 57.9 kgCO$_2$eq kg^{-1} sweaters. Overall, the average value was used in TOPSIS analyses.

For home textiles, an LCA study of eight bed sheets was selected [17]. Bed sheets were cotton, and one was a polyester and cotton blend. Textile products differ in care treatment and colour shades. The calculated average GWP was 4.2 kgCO$_2$eq for a bed sheet, and each sample had a surface weight of around 115 g m^{-2} and a surface of 7.2 m^2. Therefore, the weight of the sample is 0.8 kg, and the GWP for 1 kg of bed sheets is 5.1 kgCO$_2$eq. The study considered almost the whole life cycle, except the end-of-life.

Selected technical textile products are flame retardant (FR) treated wool and silver nanoparticles (AgNPs) treated polyester curtains. LCA study of these products looked at only use-phase and end-of-life [3]. That is why for fashion textiles, the same life stages were considered. For FR treated wool curtains average GWP of use-phase is 32 kgCO$_2$eq kg^{-1}. The average GWP of use-phase for AgNPs treated polyester curtains is four times bigger because this product requires four times more washing. The GWP of the end-of-life stage for FR treated wool and AgNPs treated polyester curtains are 1.1 and 0.8 kgCO$_2$eq kg^{-1} respectively.

These data are from reliable studies, but it should be noted that there are various gaps when comparing them. For example, the end-of-life and use-phase were considered for technical and fashion textiles, but for home textiles, almost the whole life cycle was considered. Also, the data obtained in LCA depends on the material used in the product, the country where the raw materials were obtained, and where the production and use phase took place. To consider the environmental impact of different types of fabrics, the average GWP value of several products was used.

3.1.2. Washes

The average wash times of textile products were taken from the LCA studies. The jacket is intended for ten washes [30], and the t-shirt's life span is around 52 washes [22]. For sweaters, it is between them – 28 washes [31]. The average number of washes of eight bed sheets is 68 [17]. FR treated wool curtains are designed to be washed 25 times over their lifetime, and the AgNPs treated polyester curtains need to be washed four times more [3].

3.1.3. Projected lifetime

The projected lifetime of fashion and home textiles was taken from the International fair claims guide for consumer textiles products [21]. The average lifetime of garments is 3.13 years. For home textiles, the average lifetime is 4.06 years. Some textile products were excluded from average value calculations because they were outside this study's scope. To make sure they more or less match the reality, we compared them to data from other literature sources. A survey of United Kingdom customers revealed that the average period of active use for apparel is 3.3 years [32]. For home textiles, the bed sheets are washed twice a month and last for 60 washes [17], which means their lifetime is 2.5 years. It matches the life expectancy rates of bedspreads, sheets, and pillowcases [21].

There was no data available in the scientific literature on the life span of technical textiles. Therefore, data were obtained from business and blog web pages. Flame-resistant workwear's lifetime is from one to four years, depending on the textile material used [33]. Bulletproof vests have a predicted life of five years [34]. Good quality commercial tents last up to 10 years [35]. The lifetime for sleeping bags filled with down and synthetic wadding is ten and three to four years respectively [36]. The average value was calculated based on the data mentioned above.

3.1.4. Landfilled waste and Recycled waste

The source of data for these indicators was the United States Environmental Protection Agency web page [37]. They have specific information about two groups relevant to this study – clothing and footwear, towels, sheets, and pillowcases. In 2018, 12 970 t of fashion textiles were generated, of which 9070 t were landfilled, and only 1690 t were recycled. Similar ratios are for home textiles, 1520 t were produced, 1030 t were landfilled, and 240 t were recycled.

There was no information about the technical textile stream. Therefore, assumptions were made based on data about fashion and home textiles [37]. In both cases, around 17 % are incinerated, which is why the same ratio was assumed for technical textiles. Technical textiles, such as protective textiles that are used in fields like healthcare, firefighting, law enforcement, and manufacturing, require complex recycling [3]. Thus, we assumed that technical textiles are almost three times less recycled than apparel and home textiles.

3.1.5. Origin of fabric

Around 60 % of the fibres used for fashion textile products are synthetic [25]. Among these synthetic materials, polyester is the most widely used. In the group of home textiles even more synthetic materials are used – about 70 % [25]. Also, polyester is predominant at 28 %, and nylon at 23 %. Technical textiles have a similar ratio of synthetic fibres, but specific data are not available. We assumed that most synthetics are used in the production of technical textiles. Thus, the difference between both textile groups was added to the biggest ratio.

3.1.6. Market demand

All data for the market demand criterion are comparable as the same base year was used. The global apparel market was EUR 511.39 billion in 2021 [38]. The global home and technical textile markets were valued at EUR 103.31 billion and EUR 177.53 billion respectively [39], [40].

3.1.7. Production volume

Apparel manufacturing is the leading contributor to total textile production. However, technical textile is a fast-growing sector. In EU 27, clothing accounted for 31 %, knitwear was 6 %, and underwear was 4 %. These product groups were considered fashion textile products. Workwear production was not considered because it can be fashion and technical textiles. Home and technical textile production ratios in 2021 were 14 % and 17 % respectively [41].

3.1.8. International trade

For this indicator, only data about EU were selected [41]. In 2021, exported women's clothing accounted for 24 %, men's clothing was 12 % and other garments knitted and woven

was 23 %. Home and technical textile exported ratios were 2 and 14 % respectively. It should be noted that in other countries or economic unions, the ratios could differ and affect the overall results [41].

3.1.9. Labour productivity and Value added

EU data were used as global data are not available. European Commission data for 2018 were used [26]. In 2018, the overall value added for textile-wearing apparel and accessories, technical and industrial textiles, and home textiles were 19 586, 7121, and 5507 million EUR respectively. The labour productivity for fashion textiles in 2018 was 22 thousand EUR per employee. This value is 14 % bigger than in 2015. For home textiles, labour productivity decreased by 2 % since 2015 but still was higher than fashion textiles – 29 thousand EUR per employee. Technical textile labour productivity increased by 5 % in the period 2015–2019 and was more than two times greater than fashion textiles – 47 thousand EUR per employee [26].

For the second criterion, data on the share of value added in textiles compared to total EU-27 manufacturing in 2018 was selected. The share of value added in total production for textile-wearing apparel and accessories, home textiles and technical and industrial textiles was 1.01 %, 0.28 %, and 0.37 % respectively [26].

3.1.10. Energy efficiency of production technologies

Yasin S. *et al*. summarized the energy consumption of five textile products [42]. Four products were fashion textiles, and one was home textile. One fashion product was excluded from this analysis because it is outside this study's scope. Polyester trouser manufacturing consumes 20 % of energy, polyester blouse consumes 98 %, and denim jean manufacturing uses 43 %. The home textile product was cotton curtains, and their manufacturing consumes 70 % of the total lifecycle energy.

An LCA study of wool and nylon carpets was selected to obtain data for technical textiles [43]. Data from three processes were combined to get energy usage in the manufacturing phase – raw material production, yarn production, and carpet tile production. The energy usage for nylon carpet is 18.67 MJ per functional unit, which is 73 % of total energy usage. Wool carpet production consumes 9.22 MJ per functional unit, which is 45 % of total energy usage. The average value was used in further analyses.

3.1.11. Innovation capacity

The input data of this indicator were patents filed by industry-leading countries from 2015 to 2019 in textile sectors. The countries are EU 27 Member States and countries from the European Free Trade Association, the Republic of Korea, the United States, China, Japan, Turkey, the United Kingdom, India, and Vietnam. The number of patents filed in the fashion textiles, home textiles, and technical textiles sectors was 5001, 127, and 3440 respectively [26].

3.1.12. Employment and Enterprises

Data were about EU companies because there is no data about the global situation. In 2018, the number of employees in fashion textiles, home textiles, and technical textiles was 879 689, 191 916, and 150 920 respectively. Employment in home textiles and technical textiles has increased since 2015, while in fashion textiles it has decreased by 2 %. The number of

enterprises in fashion textiles, home textiles, and technical textiles in 2018 was 120 339, 26 182, and 14 688 respectively [26].

3.2. Sensitivity analysis

After collecting the input data, sensitivity analysis was performed to determine the criteria weights. The analysis revealed that the landfilled waste, origin of fabric, and energy efficiency of production technologies have insignificant sensitivity to shifts in weight. As a result, these criteria were given the lowest weight (0.03). The environmental impact and washes criteria responded the most to the changes in weight. Therefore, it received the most significant weight (0.10). The sensitivity analysis results for environmental impact are shown graphically in Fig. 1. The other criteria were given a weight of 0.07.
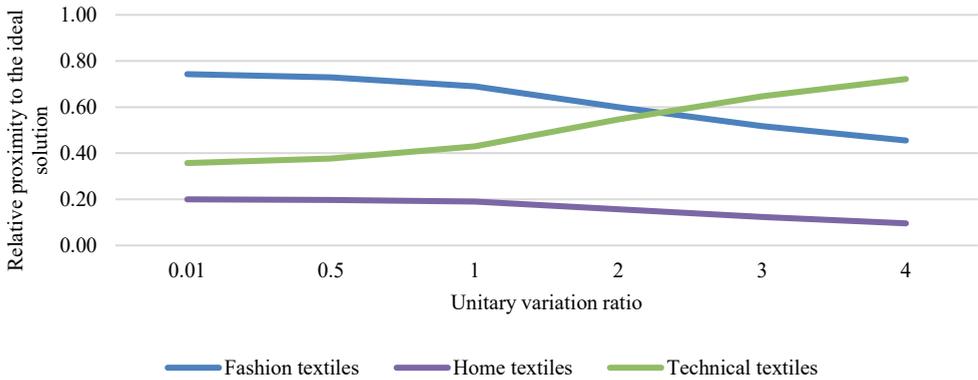
Fig. 1. Results of sensitivity analysis for environmental impact criterion.

3.3. TOPSIS

The last analysis step was TOPSIS calculations. Obtained results are shown graphically in Fig. 2. The results showed that the highest relative proximity to the ideal solution of the analysed textile product streams is for fashion textiles. It was expected because the fashion textile has eight ideal values. That means that the input value (see Table 2) met the criterion ideal value conditions (see Table 1) for eight criteria.
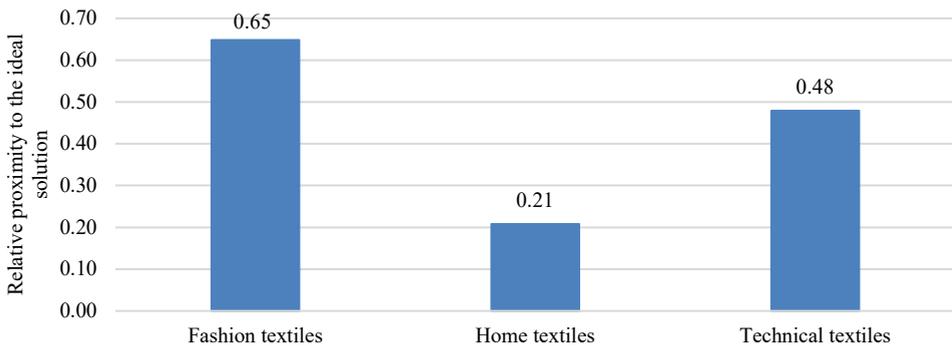
Fig. 2. Results from TOPSIS.

The technical textiles stream also received relatively good results. If we look at the input data, it has five ideal values. The lowest results are for home textiles. It was also predictable because it has eight anti-ideal values and only two ideal values. In this case, weight distribution did not significantly change the results. If all criteria had the same weights, the results would be 0.69 for fashion textiles, 0.19 for home textiles, and 0.43 for technical textiles.

4. CONCLUSIONS

The transition of the textile system to a circular economy is essential because of its high environmental impact. This study collected information on three textile product streams: fashion, home, and technical textiles. MCDA was then conducted to find the most suitable textile group for circular economy growth.

In the literature review, we gathered data on each group of textile products. Then fifteen criteria from environmental, economic, technical, and social aspects were selected for TOPSIS, and sensitivity analyses were made to determine their weights. The results indicate that the fashion textile product group has the most significant potential for circular economy development (0.65). Mainly because it is the largest textile product stream, and the development of a circular economy could be cost-effective.

These results can be used to improve existing circular economy policy. The results show that the main focus should be on apparel while developing a textile circularity policy. But technical textiles also showed relatively high circular economy potential and are a fast-growing sector, suggesting that this potential could be even higher in the future. However, before implementing a policy in a particular country or political union, more in-depth research should be done, as this study looked at the global situation and made several assumptions. The compiled data on each group of textile products is useful since it was not previously available in the scientific literature.

REFERENCES

[1] Shirvanimoghaddam K., *et al.* Death by waste: Fashion and textile circular economy case. *Science of the Total Environment* 2020:718:137317. https://doi.org/10.1016/j.scitotenv.2020.137317

[2] Ellen MacArthur Foundation. A new textiles economy: Redesigning fashion's future. 2017. [Online]. [Accessed: 18.12.2022]. Available: https://emf.thirdlight.com/file/24/uiwtaHvud8YIG_uiSTauTlJH74/A%20New%20Textiles%20Economy%3A%20Redesigning%20fashion's%20future.pdf

[3] Yasin S., Sun D. Propelling textile waste to ascend the ladder of sustainability: EOL study on probing environmental parity in technical textiles. *J Clean Prod* 2019:233:1451–1464. https://doi.org/10.1016/j.jclepro.2019.06.009

[4] Juanga-Labayen J. P., Labayen I. V., Yuan Q. A Review on Textile Recycling Practices and Challenges. *Textiles* 2022:2(1):174–188. https://doi.org/10.3390/textiles2010010

[5] Earth Overshoot Day. Past Earth Overshoot Days. [Online]. [Accessed: 13.01.2023]. Available: https://www.overshootday.org/newsroom/past-earth-overshoot-days/

[6] Tomaszewska J. Polish Transition towards Circular Economy: Materials Management and Implications for the Construction Sector. *Materials* 2020:13(22):5228. https://doi.org/10.3390/ma13225228

[7] European Commission. A new Circular Economy Action Plan. 2020. [Online]. [Accessed: 13.01.2023]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[8] United Nations. The 2030 Agenda for Sustainable Development. 2015. [Online]. [Accessed: 17.03.20122]. Available: https://www.un.org/sustainabledevelopment/development-agenda/

[9] European Environment Agency. Textiles and the environment: the role of design in Europe's circular economy. 2022. [Online]. [Accessed: 16.01.2023]. Available: https://www.eea.europa.eu/publications/textiles-and-the-environment-the

[10] Sharma A., Lakshmanan R., Nayyar M. Technical Textiles: The Future of Textiles. 2020. [Online]. [Accessed: 16.01.2023]. Available: https://www.investindia.gov.in/siru/technical-textiles-future-textiles

[11] Zlaugotne B., *et al.* Multi-Criteria Decision Analysis Methods Comparison. *Environmental and Climate Technologies* 2020:24(1):454–471. https://doi.org/10.2478/rtuect-2020-0028

[12] Acar E., Kiliç M., Güner M. Measurement of sustainability performance in textile industry by using a multi-criteria decision making method. *Textile and Apparel* 2015:25(1):3–9. [Online]. [Accessed: 18.01.2023]. Available: https://dergipark.org.tr/en/pub/tekstilvekonfeksiyon/issue/23647/251904

[13] Jia F., *et al.* The circular economy in the textile and apparel industry: A systematic literature review. *J Clean Prod* 2020:259:120728. https://doi.org/10.1016/j.jclepro.2020.120728

[14] Wagner M. M., Heinzel T. Human Perceptions of Recycled Textiles and Circular Fashion: A Systematic Literature Review. *Sustainability* 2020:12(24):10599. https://doi.org/10.3390/su122410599

[15] Moazzem S., *et al.* Environmental impact of discarded apparel landfilling and recycling. *Resour Conserv Recycl* 2021:166:105338. https://doi.org/10.1016/j.resconrec.2020.105338

[16] Aus R., *et al.* Designing for circular fashion: integrating upcycling into conventional garment manufacturing processes. *Fashion and Textiles* 2021:8(1):34. https://doi.org/10.1186/s40691-021-00262-9

[17] De Saxce M., Pesnel S., Perwuelz A. LCA of bed sheets – some relevant parameters for lifetime assessment. *J Clean Prod* 2012:37:221–228. https://doi.org/10.1016/j.jclepro.2012.07.012

[18] Ranasinghe L., Jayasooriya V. M. Ecolabelling in textile industry: A review. *Resources, Environment and Sustainability* 2021:6:100037. https://doi.org/10.1016/j.resenv.2021.100037

[19] Mensah J. Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent Social Sciences* 2019:5(1):1653531. https://doi.org/10.1080/23311886.2019.1653531

[20] Manshoven S., *et al.* Textiles and the environment in a circular economy. 2019. [Online]. [Accessed: 24.01.2023]. Available: https://ecodesign-centres.org/wp-content/uploads/2020/03/ETC_report_textiles-and-the-enviroment-in-a-circular-economy.pdf

[21] Drycleaning Institute of Australia Ltd. International fair claims guide for consumer textiles products. 2015. [Online]. [Accessed: 25.01.2023]. Available: https://irp-cdn.multiscreensite.com/670b4da8678441db9ca09d24ced7de7c/files/uploaded/Fair%20Claims%20Guide.pdf

[22] Pesnel S., Payet J. Product Environmental Footprint Category Rules (PEFCR) T-shirts. [Online]. [Accessed: 25.01.2023]. Available: https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_tshirt.pdf

[23] Šajn N. Textiles and the environment. 2022. [Online]. [Accessed: 16.11.2022]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729405/EPRS_BRI(2022)729405_EN.pdf

[24] Botta V., Cabral I. Durable, repairable and mainstream. How ecodesign can make our textiles circular. [Online]. [Accessed: 25.01.2023]. Available: https://ecostandard.org/wp-content/uploads/2021/04/ECOS-REPORT-HOW-ECODESIGN-CAN-MAKE-OUR-TEXTILES-CIRCULAR.pdf#page=9

[25] Manshoven S., *et al.* Plastic in textiles: potentials for circularity and reduced environmental and climate impacts. 2021. [Online]. [Accessed: 26.01.2023]. Available: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts

[26] European Commission. Data on the EU textile ecosystem and its competitiveness: Final report. 2021. [Online]. [Accessed: 22.02.2023]. Available: https://data.europa.eu/doi/10.2873/23948

[27] Valtere M., *et al.* The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran. *Environmental and Climate Technologies* 2022:26(1):658–669. https://doi.org/10.2478/rtuect-2022-0050

[28] Li P., *et al.* Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights. *Environ Monit Assess* 2013:185(3):2453–2461. https://doi.org/10.1007/s10661-012-2723-9

[29] Gonçalves A., Silva C. Looking for sustainability scoring in apparel: A review on environmental footprint, social impacts and transparency. *Energies (Basel)* 2021:14(11):3032. https://doi.org/10.3390/en14113032

[30] Gore & Associates W. L. Life Cycle Assessment of a GORE branded waterproof, windproof and breathable jacket. 2013. [Online]. [Accessed: 24.01.2023]. Available: https://www.gore-tex.com/sites/default/files/assets/Gore_LCA_summary_report.pdf

[31] Nolimal S. Life Cycle Assessment of Four Different Sweaters. *DePaul Discoveries* 2018:7(1). [Online]. [Accessed: 24.01.2023]. Available: https://via.library.depaul.edu/depaul-disc/vol7/iss1/9

[32] Cooper T., Claxton S. Garment failure causes and solutions: Slowing the cycles for circular fashion. *J Clean Prod* 2022:351:131394. https://doi.org/10.1016/j.jclepro.2022.131394

[33] LAPCO FR, FR Clothing Wash Expectancy – Useful Life. 2019. [Online]. [Accessed: 26.01.2023]. Available: https://www.lapco.com/blogs/fr-education-guides/how-many-times-can-you-wash-fire-retardant-clothing

[34] Collective Data. Why Bulletproof Vests Expire? 2020. [Online]. [Accessed: 26.01.2023]. Available: https://collectivedata.com/articles/why-bulletproof-vests-expire/

[35] Economy Tent International. Everything You Need to Know about Commercial Tents. [Online]. [Accessed: 26.01.2023]. Available: https://economytent.com/everything-you-need-to-know-about-commercial-tents/

[36] Outdoorline. Down or synthetic insulation? [Online]. [Accessed: 26.01.2023]. Available: https://www.outdoorline.sk/en/content/down-or-synthetic-insulation

[37] United States Environmental Protection Agency. Nondurable Goods: Product-Specific Data. 2021. [Online]. [Accessed: 15.11.2022]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/nondurable-goods-product-specific-data#ClothingandFootwear

[38] Research and Markets. $605.4 Billion Worldwide Apparel Industry Report to 2031 – Identify Growth Segments for Investment. 2022. [Online]. [Accessed: 27.01.2023]. Available: https://www.globenewswire.com/en/news-release/2022/04/22/2427162/28124/en/605-4-Billion-Worldwide-Apparel-Industry-Report-to-2031-Identify-Growth-Segments-for-Investment.html

[39] Research and Markets. Global Home Textile Market Report 2022: Expected Value of $145.05 Billion by 2026. 2022. [Online]. [Accessed: 27.01.2022]. Available: https://www.globenewswire.com/en/news-release/2022/07/05/2473738/28124/en/Global-Home-Textile-Market-Report-2022-Expected-Value-of-145-05-Billion-by-2026.html

[40] The Business Research Company. Technical Textiles Global Market Report 2022. 2022. [Online]. [Accessed: 27.01.2023]. Available: https://www.reportlinker.com/p06313445/Technical-Textiles-Global-Market-Report.html

[41] EURATAX. Facts and key figures 2022 of the European textile and clothing industry. 2022. [Online]. [Accessed: 30.01.2023]. Available: https://euratex.eu/wp-content/uploads/EURATEX_FactsKey_Figures_2022rev-1.pdf

[42] Yasin S., *et al*. A case study of life cycle inventory of cotton curtain. 2014. [Online]. [Accessed: 30.01.2023]. Available: https://hal.archives-ouvertes.fr/hal-01984356

[43] Sim J., Prabhu V. The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States. *J Clean Prod* 2018:170:1231–1243. https://doi.org/10.1016/j.jclepro.2017.09.203

CO$_2$ Storage in Logging Residue Products with Analysis of Energy Production Scenarios

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Abstract – **Woody logging residues produced by logging activities are currently an underutilised resource that is mainly burned for energy production or left in the forest to decay, thus releasing CO$_2$ into the atmosphere. This resource could be used to manufacture long-lasting products and store a significant amount of CO$_2$, promoting CO$_2$ valorisation in rural areas. In this study, potential use for logging residues is proposed – the production of low-density wood fibreboard insulation panels. The new material's potential properties, manufacturing method and combined heat and power (CHP) plant parameters were proposed. The potential climate benefits of the new product were analysed using various biogenic carbon accounting methods. As energy production for manufacturing can be a significant source of emissions, possible energy production scenarios were analysed for manufacturing the product. However, an economically and environmentally viable energy production scenario should be chosen. By conducting a multi-criteria analysis, three possible energy production scenarios were analysed – wood biomass CHP plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with Solar photo-voltaic (PV) panels. The scenarios were analysed in terms of technological, economic, and environmental performance to determine the best strategy in this case.**

Keywords – **CO$_2$ storage; energy production; logging residues; wood products.**

1. INTRODUCTION

Forestry practices produce large amounts of waste and residues from the harvestable yield. This can present significant management problems, as the discarded biomass can hurt the environment. Meanwhile, sustainable energy sources and raw material feedstock are required with increasing global population and rising demand for construction products and materials. Forestry waste and logging residues are under-utilized resources for energy and material production. To date, there has been little activity to utilise these resources in a 'low carbon' way. It is estimated that for every cubic meter of logged wood material removed, a cubic meter of wastes and residues (e.g., stumps, branches, greenery) is left in the forest. Currently, of all wood-derived biomass produced globally, 20 % can be accounted as primary production loss left in the woods to decay, which could instead be used as a feedstock for a variety of products, including the production of fuels, polymers and building materials and products [1].

Wood, like products made from it, has a significant advantage over other building materials – they are an essential source of CO$_2$ sequestration. It has been observed that there exists a direct correlation between the amount of CO$_2$ sequestered and the amount of wood-derived

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biomass harvested to produce high-added value products – with increasing amounts of wood harvested or rising efficiency of timber used, the amount of carbon sequestration is also increased [2]. The overall decarbonisation solutions can be achieved if sustainable carbon cycles, including using Carbon Capture and Utilisation technologies, are implemented (see Fig. 1) [3]–[6].
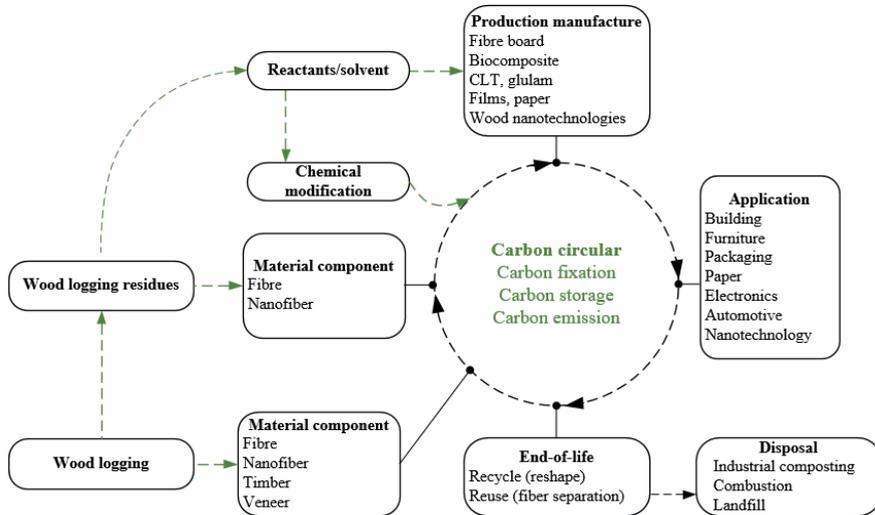

Fig 1. The sustainable carbon cycle of wood logging residues [1].

In the wood-based product sector, significant potential for CO_2 sequestration can be attributed to the production of wood-based panels and engineered wood products [7], [8]. In a 2017 study about carbon storage in wood products, the carbon sequestration potential of three different wood-based panels was reviewed – oriented strand board (OSB), particleboard (PB) and medium density fibreboard (MDF). According to the IPCC methodology, all three of these products are included in the national inventory reports as harvested wood products that store carbon, thus decreasing the overall CO_2 balance in the atmosphere. It was calculated that a cubic meter of PB and OSB sequester 720 kg of CO_2 each and that a cubic meter of MDF sequesters 820 kg of CO_2, considering the number of emissions from material production [9].

However, despite this advantage, producing such panels is quite an energy-intensive process. The Best Available Techniques (BAT) Reference Document to produce Wood-based Panels states that the average amount of thermal energy required to produce one cubic meter of the material is 0.955 MWh for PB, 0.4 MWh for OSB and 1.65 MWh for MDF panels. The average amount of electrical energy required to produce one cubic meter of the material is 0.155 MWh for PB, 0.115 MWh for OSB and 0.505 MWh for MDF panels [9], [10]. In turn, producing such thermal insulation materials as Ecowool and mineral wool requires 0.00416 MWh and 0.200 MWh of electricity per cubic meter of product. Although rigidboards are popular insulation material, they are mostly produced from expanded polystyrene or polyurethane foam – both are produced from fossil resources eliminating the opportunity to store CO_2 in such products. Nevertheless, rigid and flexiboards from wood fibres are becoming more popular. Production technology of such materials is similar to other wood fibre materials, in detail described further in this paper.

Although the CO_2 sequestration benefits of one cubic meter of rigid board insulation material will be lower than that of OSB, PB and MDF panels, considering the lower density of wood in the material, it will require less energy and raw materials to manufacture. The low-efficiency and uninsulated buildings in Latvia and many other countries are still tall, meaning that building insulation materials will remain a high-demand product for the foreseeable future. There is a wide range of insulation materials available today, each with its advantages and disadvantages. However, modern consumers care not only about the physical and mechanical properties of the material but also about the environmental impact. Manufacturing insulation materials could become one of the future opportunities of the forestry industry of Latvia. Generating by-products and residues in the harvesting and manufacturing processes is inevitable. Currently, forestry companies mainly use these by-products to produce energy or sell them to other companies. Exporting these by-products is still inefficient since they are now sold as low-added value products. As companies in the forestry sector move to increase the efficiency and productivity of their production, the utilisation of wastes and residues previously considered low value is becoming an increasingly attractive option. Using these by-products to manufacture thermal insulation is one of the potential solutions for increasing their value [11], [12].

Mitigation of CO_2 emissions has become a top question in the last decades. Therefore, understanding processes within rural CO_2 economy sectors, factors, interconnections and effects on the environment and nature quality and guidelines for future activities are crucial. Valorisation of CO_2, including direct capture and utilization, transformed CO_2 utilization or pre-processed CO_2 utilization, can positively affect the reduction of CO_2 emission and the development of rural areas [3]–[6]. The changes in wood waste treatment practices and production of the rigid board from wood logging residues can have a positive effect on mitigating CO_2 emissions, providing its storage in the products. This work aims to analyse the environmental impact of this insulating material. Using an underestimated resource to produce thermal insulation material can be viable from economic and technological perspective. The practice could be favourable from product demand, and raw material supply perspective by adding value to wood value-chain.

2. METHODS AND METHODOLOGY

For this study, the production of rigid board wood insulation material was chosen. The production methodology consists of steps like a description of the production process and needed feedstock calculation of the amount of CO_2 that can be stored in the final product. As for the energy sources for the rigid board production. Three different scenarios have been compared using the multicriteria analysis method. All steps of the methodology are seen in Fig. 2.
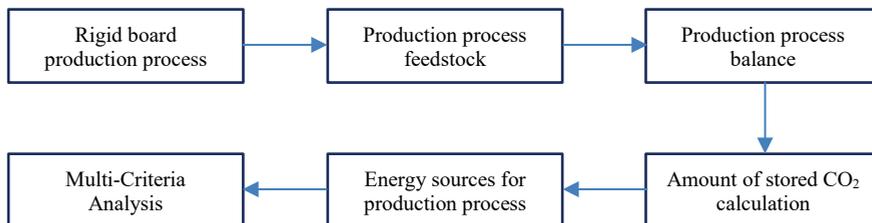

Fig. 2. Algorithm of the methodology.

The rigid board is produced similarly to other wood fibre boards e.g., MDF and LDF. The same dry process is used for refining the dried wood fibres derived from wood chips. After drying, the material goes through forming, pressing and profiling. A simplified manufacturing process of rigid board insulation panels is shown in Fig. 3. The refined and dried wood fibres are mixed with resin, formed into a mat, and then pressed and cured. Curing occurs by passing steam through the mat to heat it slightly. In comparison to general MDF production, the working pressure is lower and process does not require heated press. The slight temperature increase and the small amount of water cure the resin. The resin used for rigid board production is exclusively pMDI (polymeric methylene diphenyl diisocyanate). Rigid board is produced in various thicknesses ranging 18–244 mm and in densities ranging 100–220 kg/m^3. It is mainly used for insulation purposes, and the raw boards are passed through a profiler to produce a tongue-and-groove finish [10].
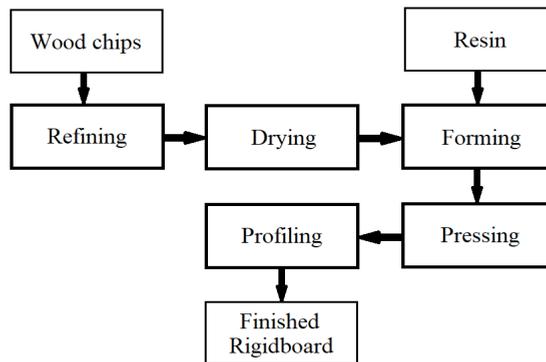
Fig. 3. Simplified rigidboard manufacturing process [10].

The primary feedstock for manufacturing the new rigidboard is logging residues, mainly from coniferous trees, the dominant tree group harvested in Latvia. The logging residues used for the production of chips will especially be branches, smaller logs and possibly stumps that are not used in conventional production. It is assumed that all needles and other greenery will fall off or be removed from the feedstock while in storage and manufacturing. To produce fibreboard insulation panels, wood fibres of strong and uniform quality must be obtained. Although MDF and other fibreboard producers traditionally use roundwood as a raw feedstock, novel methods of cleaning and sorting waste wood or production residues from other woodworking industries have enabled alternative sources of wood materials on dedicated production lines [10]. A 2013 study about the chase characteristics of wood chips produced from logging residues concluded that wood chips produced from logging residues have a moisture content of 50 % and are suitable for use in small and medium size boilers [13]. It is assumed that the wood chips obtained from logging residue feedstock will be of sufficient quality to produce fibreboard panels.

The material balance of the new fibreboard insulation panel is shown in Table 1. Material density is assumed maximum for rigid board production from the BAT Reference Document for Wood-based Panels [10]. Material balance was chosen based on fibreboard and insulation board data from the Forest Product Conversion Factors document [14], assuming an increased bark and decreased wood content. The weight content of bark, binders and fillers, moisture and wood in one cubic meter of the finished insulation panel were calculated based on the chosen material density and material balance.

For the new fibreboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels [10], modified for rigid board production (Fig. 2).

TABLE 1. FIBREBOARD INSULATION MATERIAL BALANCE

	Content, kg/m^3	Balance, %	Source
Density	220	100	[10]
Bark	6.6	3	[14]
Binders and fillers	11	5	[14]
Moisture	13.2	6	[14]
Wood	189.2	86	[14]

It is assumed that the new plant would produce 300 000 m^3 of fibreboard insulation material annually, based on average plant capacities in the industry [10]. To calculate the specific amounts of heat and electric energy needed to produce one cubic meter of the material, existing insulation material manufacturing plant data was used. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW [15] and operates for 8000 hours annually, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce one cubic meter of fibreboard insulation material. Energy consumption for the most energy-intensive manufacturing processes is shown in Table 2. The drying of the wood fibres consumes the most energy, mainly in the form of thermal energy, as the fibres need to be dried from a moisture content nearing 100 % to 5 %. The dryers also need to be ventilated, using mechanical ventilators that consume electricity. The second most energy-intensive process is refining the fibres, which requires powerful motors that consume the most electricity. Thermal energy is also needed for refining to supply hot steam for cooking and washing wood chips. The pressing of the fibreboard mat requires thermal energy in the form of steam and electricity for the press rollers; however, for the production of rigid board insulation, the energy consumption is minimised, as the temperature required is relatively low. Lastly, all other processes requiring electricity are grouped, such as chipping, sawing and profiling [10].

TABLE 2. ENERGY CONSUMPTION FOR PRODUCTION

Manufacturing process	Electricity, MWh/m^3	Thermal energy, MWh/m^3
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	–
Total	0.13	0.26

To calculate the possible amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products were reviewed and used. Many different technical standards for Life Cycle Analysis (LCA) with other methods and approaches for carbon accounting. Still, in this case, only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485,

PEF) and have stronger links to government regulation [16]–[18]. As there currently exists no scientific consensus on which standard and method are the most appropriate for use, an average value derived from all standards was proposed.

The initial calculation for CO_2 stored in the material is assumed to be the same for all standards and is calculated [17]:

$$mCO_2 = m_{dry}(\text{timber}) \cdot C_f \cdot \frac{m.mCO_2}{m.m_C},$$ (1)

where
mCO_2	mass of CO_2 sequestered, $kgCO_2$;
$m_{dry}(\text{timber})$	dry weight of timber in the finished product, kg;
C_f	percentage of carbon in dry matter (for timber = 0.5);
$m.mCO_2$	molecular mass of CO_2 = 44 g/mol;
$m.m_C$	atomic mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO_2, Eq. (1) becomes:

$$mCO_2 = m_{dry}(\text{timber}) \cdot 0.5 \cdot \frac{44}{12} = m_{dry}(\text{timber}) \cdot 1.833,$$ (2)

where mCO_2 is the mass of CO_2 sequestered in the finished product and $m_{dry}(\text{timber})$ is the dry weight of timber in the finished product.

Only the CO_2 sequestered from the wood and bark content for the new product is calculated. The carbon content for bark is assumed to be the same as wood (50 %).

To maximise the CO_2 storage potential of the new fibreboard insulation material, the energy production sources for the manufacturing process need to be reviewed and analysed, as energy production is the single most significant source of emissions and can potentially offset the avoided CO_2 stored in the product material. Indeed, producing heat and power from the most environmentally friendly renewable sources would be the best way to minimise emissions from manufacturing. However, this may not always be the most technologically and economically viable option. Thus, energy production for product manufacturing needs to be assessed from an environmental point of view while considering the technological and economic aspects. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity [16], current trends in the sector and possible future technologies. Technological, economic and environmental data for the three proposed scenarios are shown in Table 3. The capacities of the energy production plants were chosen according to the required minimum heat capacity of the manufacturing plant of 10 MW, as all the process heat needs to be produced on-site to meet heat and steam requirements. The electrical power of the energy production plant can be lower than the electrical demand of the manufacturing plant, as electricity can also be supplied from the grid. The first proposed scenario is to produce heat and power with a biomass combined heat and power (CHP) plant, which would use wood chips as fuel. The chosen CHP technology is a wood chip boiler combined with a steam turbine. The second proposed scenario is a natural gas CHP plant with a gas turbine technology well suited for industrial processes. The third proposed scenario is a wood biomass combustion plant (CP) producing only thermal energy, using wood chips as fuel, combined with Solar Photo-voltaic (PV) panels for electricity production.

To evaluate environmental impacts, five different emission values were considered for each scenario: NO_X (nitrogen oxides), CO (carbon monoxide), VOC (volatile organic compounds), PM (particulate matter) and CO_2 (carbon dioxide).

TABLE 3. TECHNOLOGICAL, ECONOMIC AND ENVIRONMENTAL PARAMETERS OF PROPOSED ENERGY PRODUCTION SCENARIOS

Parameter	Wood biomass CHP	Natural gas CHP	Wood biomass CP + PV panels	Sources
Electrical capacity, MWe	5	7.5	4	[19], [20], [21]
Thermal capacity, MWth	12	10.7	12	[19], [20]
Electrical efficiency, %	25	29.2	–	[20], [22]
Thermal efficiency, %	60	41.4	85	[20], [22]
Total efficiency, %	85	70.6	85	[20], [22]
Capital costs, EUR/kW[a]	3310	1510	965[b]	[23]
O&M costs, %CAPEX	2	2.5	2[b]	[23]
Fuel cost, EUR/MWh	25	81.2	25	[24], [25]
NO_X emissions, g/MWh[c]	29	27	9.1	[20], [26]
CO emissions, g/MWh[c]	8	31.5	2.5	[20], [26]
VOC emissions, g/MWh[c]	0	27	0	[20], [26]
PM emissions, g/MWh[c]	44	0	13.6	[20], [26]
CO_2 emissions, kg/MWh[d]	0	202	0	[27]

[a] Based on the electrical capacity for CHP and thermal capacity for CP
[b] Does not include the cost of PV panels
[c] Applies to electricity produced for CHP and thermal energy for CP
[d] Applies to both electrical and thermal energy produced

The capital costs of the standalone biomass combustion plant are assumed to be 30 % lower than the costs of the same thermal capacity CHP plant. Still, they are recalculated according to the thermal capacity of the combustion plant. Similarly, emission levels for the standalone biomass combustion plant are assumed to be the same as for the biomass CHP plant. Still, they are recalculated for a total thermal efficiency of 85 % instead of 60 % and apply only to the thermal energy produced.

The capital costs and O&M costs for the Solar PV panels are chosen according to the peak capacity of Solar PV panel installation. A Solar PV panel installation with an electrical capacity of 4 MWe is assumed to have a peak capacity of 5.4 MWp. The capital costs for an installation of this size are 510 EUR/kWp, and O&M costs 6.5 EUR/kWp [21].

A multicriteria analysis using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method compares the three energy production scenarios. Using the TOPSIS method, the proposed scenarios or alternatives are evaluated for the ideal possible solution. The alternative that is the closest to the ideal solution is considered to be the best scenario [28]. The criteria were selected according to the opinion of experts whose work profile is directly related to construction, sustainability and innovation, as well as the literature analysis. The criteria chosen for the analysis are shown in Table 4. The values of the criteria were calculated using data from Table 3 and applied to the manufacturing plant's selected electrical and thermal energy demand parameters, with the annual plant production

capacity of 300 000 m^3 of fibreboard insulation material. The criteria values were calculated relative to one cubic meter of the finished product.

To perform the multicriteria analysis, the criteria weights need to be determined. The criteria weights were determined using the Analytical Hierarchy Process (AHP) method [28]. The criteria were first ranked in importance, prioritising economic and technological criteria, and then ranking the environmental criteria by their global warming potential. The weights of each criteria were then determined according to their rank, consequently comparing them to each other.

TABLE 4. CHOSEN CRITERIA FOR THE MULTICRITERIA ANALYSIS

Technological criteria	Economic criteria	Environmental criteria
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NO$_X$ emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	VOC emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO$_2$ emissions, kg/m^3

With the obtained criteria weights, the results of the multicriteria analysis were calculated. The result is shown as a relative closeness coefficient to the ideal solution. The results can have a value ranging from 0 to 1, with the ideal solution being a value of 1. The closer the coefficient of a proposed alternative is to the maximum value of 1, the closer it is to the ideal solution.

3. RESULTS

The amount of stored biogenic CO$_2$ in the new fibreboard insulation material for the eight different accounting standards is shown in Table 5. The stored amount has been calculated for one cubic meter of the new fibreboard insulation material.

TABLE 5. STORED BIOGENIC CO$_2$ DEPENDING ON ACCOUNTING STANDARD

Technical standard	Stored CO$_2$, kg/m^3	Source
EN-15804 (2012)	359	[18]
ISO/DIS-21930 (2015)	251	[29]
EN-15804 (2012) +A1:2013	359	[18]
CEN/TR-16970 (2016)	359	[18]
EN-16485 (2014)	359	[18]
ISO/TS-14067 (2013)	90	[30]
PEF v2.2 (2016)	90	[30]
PAS-2050 (2011)	291	[31]

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014) the calculated amount of stored CO$_2$ is the same, as they are all based om the same standard of EN-15804 (2012) and assume that the amount is calculated with the formula shown in Eq. (2), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2 (2016) standards are based on the previous ISO-14040/44 standard for LCA, and do not differ in calculating the stored CO$_2$.

Standards-based on the EN-15804 standard offer the highest amount of CO_2 stored in one cubic meter of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 90 $kgCO_2/m^3$. Considering all standards, an average value of 270 $kgCO_2/m^3$ stored can be assumed as the final result if no single carbon accounting method is chosen.

The calculated criteria values and weights for the multicriteria analysis of three different energy production scenarios are shown in Table 6.

TABLE 6. CRITERIA VALUES AND WEIGHTS

	Wood biomass CHP	Natural Gas CHP	Wood biomass CP + PV panels	Criteria weight
Fuel energy content, GJ/m^3	1.56	2.26	1.10	0.079
Capital costs, EUR/m^3	12.68	38.01	8.45	0.210
Fuel costs, EUR/m^3	55.17	37.75	47.80	0.288
O&M costs, EUR/m^3	1.10	0.94	0.89	0.152
Bought/sold electricity, EUR/m^3	3.84	−9.45	19.77	0.110
NO_X emissions, g/m^3	3.14	4.95	2.36	0.028
CO emissions, g/m^3	0.86	5.78	0.64	0.016
VOC emissions, g/m^3	0	4.95	0	0.020
PM emissions, g/m^3	4.7	0	3.5	0.040
CO_2 emissions, kg/m^3	0	90	0	0.057

The results of the multicriteria analysis of three different energy production scenarios are shown in Fig. 4.
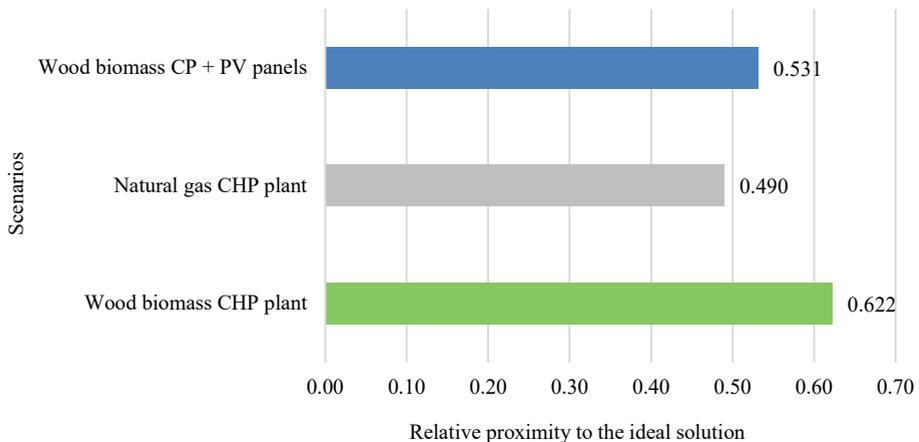
Fig. 4. Multicriteria analysis results.

The results of the multicriteria analysis show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). In second place are the wood biomass combustion plant and Solar PV panel scenario (0.531), barely beating out the natural gas CHP plant scenario (0.490). While currently, the multicriteria analysis shows that the fossil resource use scenario of natural gas is relatively close in valuation compared to the

renewable resource use scenarios of wood biomass, it is evident that the evaluation of the natural gas CHP plant scenario could decrease in the future, as the world moves to use more renewable resources. Nevertheless, the natural gas CHP plant scenario still needs to be reviewed and considered, so it can be clearly shown that there are better renewable resource alternatives, which are the wood biomass CHP and combustion plants. To emphasise this further, more detailed studies should be carried out, which should consider both quantitative and qualitative data, including data and opinions of experts and companies in the field. Social and political aspects should also be reviewed in further studies. This, in turn, could significantly impact the evaluations of the different energy production scenarios, possibly increasing the assessment of the renewable energy source scenarios to mark them as the clear favourite over fossil resource use.

4. CONCLUSION

This study proposed a new possible wood fibreboard insulation material product made from a currently underutilised wood resource – logging residues. The material balance of the new product was presented, along with the manufacturing technology, manufacturing plant capacity and energy resource demands. The possible amount of CO_2 stored in the new product was calculated and reviewed using eight standards and their methods for biogenic carbon accounting.

The amount of stored CO_2 in the material varies considerably depending on the accounting method. Ideally, one of the eight possible standards should be chosen and prioritised. If no standard can be selected, an average value of stored CO_2 calculated from all eight standards could be proposed.

As the single largest source of emissions for the manufacturing of the new product is energy production, different energy production scenarios were analysed based on current trends in the industry. The scenarios were analysed regarding technological, economic, and environmental performance. Renewable energy scenarios should be considered a priority. However, fossil resource use was also considered, as the technical and financial benefits might outweigh the environmental disadvantages.

Three energy production scenarios were analysed: wood biomass combined heat and power (CHP) plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with solar photo-voltaic (PV) panels. The analysis results show the wood biomass CHP plant as the best scenario for energy production for the new manufacturing plant. However, the other scenarios are relatively close in evaluation.

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REFERENCES

[1] Montanari C., Olsén P., Berglund L. A. Sustainable Wood Nanotechnologies for Wood Composites Processed by In-Situ Polymerization. *Front. Chem.* 2021:9:1–12. https://doi.org/10.3389/fchem.2021.682883
[2] Blumberga D., *et al*. Forest biomass – new products and technologies. Riga: Riga Technical University, Institute of Energy Systems and Environment, 2016.
[3] Terjanika V., Pubule J. Barriers and Driving Factors for Sustainable Development of CO_2 Valorisation. *Sustainability* 2022:14(9):5054. https://doi.org/10.3390/su14095054

[4] Terjanika V., *et al*. Analysis of CO₂ Valorisation Options for Regional Development. *Environmental and Climate Technologies* 2021:25(1):243–253. https://doi.org/10.2478/rtuect-2021-0017.

[5] Terjanika V., Blumberga D., Pubule J. Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia. *Proceedings of the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON* 2021. https://doi.org/10.1109/RTUCON53541.2021.9711727.

[6] Singh T., *et al*. Emerging technologies for the development of wood products towards extended carbon storage and CO₂ capture. *Carbon Capture Science & Technology* 2022:4:100057. https://doi.org/10.1016/j.ccst.2022.100057

[7] Xu X., *et al*. Bamboo construction materials: Carbon storage and potential to reduce associated CO₂ emissions. *Science of the Total Environment* 2022:814:152697. https://doi.org/10.1016/j.scitotenv.2021.152697

[8] Tripathi N., *et al*. Biomass waste utilisation in low-carbon products: harnessing a significant potential resource. *Npj Climate and Atmospheric Science* 2019:2:35. https://doi.org/10.1038/s41612-019-0093-5

[9] Kazulis V., *et al*. Carbon storage in wood products. *Energy Procedia* 2017:128:558–563. https://doi.org/10.1016/j.egypro.2017.09.009

[10] Raunkjaer Stubdrup K., *et al*. Best Available Techniques (BAT) Reference Document for the Production of Wood-based Panels. Seville: JRC, 2016.

[11] Veitmans K., Grinfelds U. Wood fibre insulation material. *Research for Rural Development* 2016:2:91–98.

[12] Vamza I., *et al*. Bioresource utilization index – A way to quantify and compare resource efficiency in production. *Journal of Cleaner Production* 2021:320:128791. https://doi.org/10.1016/j.jclepro.2021.128791

[13] Gruduls K., *et al*. 2013. Characteristics of wood chips from logging residues and quality influencing factors. *Research for Rural Development* 2013:2:49–54.

[14] FAO, ITTO, United Nations. Forest product conversion factors. Rome: FAO, 2020.

[15] Dieffenbacher GmbH. Fibre Insulation Board lines [Online]. [Accessed 20.04.2022]. Available: https://www.environmental-expert.com/products/fibre-insulation-board-lines-190613

[16] Tellnes L. G. F., *et al*. Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: A review study for construction materials based on forest products. *iSEF – Italian Society of Silviculture and Forest Ecology* 2017:10(5):815–823. https://doi.org/10.3832/ifor2386-010

[17] Pubule J., *et al*. Analysis of the environmental impact assessment of power energy projects in Latvia. *Management of Environmental Quality* 2012:23(2):190–203. https://doi.org/10.1108/14777831211204930.

[18] BRE Ltd. BRE Global Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012+A1:2013. Watford: BRE Group, 2014.

[19] Balkan Green Energy News. 5 MWe biomass cogeneration plant officially opened in the city of Slatina. 2019 [Online]. [Accessed 20.04.2022]. Available: https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/

[20] U.S. Department of Energy. Combined Heat and Power Technology Fact Sheet Series: Gas turbines. Washington: DoE, 2016.

[21] Danish Energy Agency. Technology Data for Energy Plants for Electricity and District Heating generation. Copenhagen: DEA, 2019.

[22] Abbas T., Issa M., Ilinca A. Biomass Cogeneration Technologies: A Review. *Journal of Sustainable Bioenergy Systems* 2020:10(1):1–15. https://doi.org/10.4236/jsbs.2020.101001

[23] Tsiropoulos I., Tarvydas D., Zucker A. Cost development of low carbon energy technologies. Luxembourg: Publication Office of European Union, 2018.

[24] Zalamane D. Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā ar dabasgāzi (The price of wood chips is rising, heating with wood chips is 5 times cheaper than with natural gas.). 2022 [Online]. [Accessed 20.04.2022]. Available: https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka-.a155970/ (in Latvian)

[25] 'Latvijas gaze' brīdina par dabasgāzes biržas cenas trīskāršu pieaugumu aprīlī ('Latvian gas' warns of a threefold increase in natural gas exchange prices in April). 2022 [Online]. [Accessed 20.04.2022] Available: https://www.lsm.lv/raksts/zinas/ekonomika/latvijas-gaze-bridina-par-dabasgazes-birzas-cenas-triskarsu-pieaugumu-aprili.a446800/ (in Latvian)

[26] Darrow K., *et al*. Catalogue of CHP technologies. Boston: EPA, ICF International, 2017.

[27] Cabinet of Ministers. Methodology for calculating greenhouse gas emissions. *Latvijas Vestnesis* 2018:18.

[28] Ishizaka A., Nemery P. Multi-criteria Decision Analysis: Methods and Software. USA: Wiley, 2013.

[29] American Center for Life Cycle Assessment. ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017. Washington: ACLCA, 2019.

[30] European Commission, Joint Research Centre, Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook. General guide for Life Cycle Assessment. Detailed guidance. Luxembourg: Publications Office of the European Union, 2010.

[31] British Standards Institution. 2011. PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
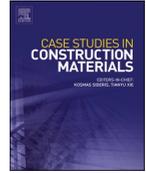
Case study

Recycled cross-laminated timber as a low environmental impact alternative to virgin material: Latvia case study

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A R T I C L E   I N F O

A B S T R A C T

Building with wood has become more popular and so has the circularity concept and carbon storage in products. This study aims to analyse the life cycle impacts of cross-laminated timber (CLT) recycling. Functional unit of 1 m^3 was chosen for the CLT and recycled cross-laminated timber (ReCLT) comparison. For the life cycle assessment, the ReCiPe methodology was used allowing to calculate midpoint and endpoint accumulated impacts of both ReCLT and CLT, therefore allowing for the best comparison. Overall, the ReCLT showed significantly reduced environmental impacts in endpoint categories from 50 % to 80 % reduction in the single score evaluation. Although midpoint impacts showed mostly reduced environmental impacts, e.g., global warming, land use and others, the water eutrophication – both marine and freshwater, leading to think for improvements in the recycling process.

1. Literature review

Building sector constitutes for 40 % of annual global carbon dioxide emissions, largely due to the used construction materials, especially the production and use of steel and concrete – both being known as materials with high environmental footprint [1]. Therefore, The European Green Deal and other initiatives strive to make changes in the sector by setting goals to reach lower emission levels. The goals could be reached by improving the efficiency of production technologies or by developing and using new materials with lower emission footprint. Cross laminated timber (CLT) has been on the market for around 30 years and it has shown to be a promising alternative material to concrete and steel as CLT`s mechanical properties are sufficient for it to be a structural material and the cost for building with CLT are competitive to the popular building techniques with steel and concrete [2]. Building with CLT have been gaining traction for climate reasons – for the renewable material and carbon storage potential, replacing energy intensive concreate production [3]. Building with wood has regained its popularity with the invention of CLT, timber use cases have been expanded to mid-rise buildings [4].

With The European Green Deal in place, even the climate beneficial CLT buildings have been subjected to thinking more about circularity in this building sector. Circularity comes into building with CLT in multiple ways. It is important to include CLT in the overall building recycling efforts aimed at better reuse of the materials from demolished buildings. Although building with CLT is relatively new, it is expected that in the years to come the need for recycling of post-consumer CLT materials will arise [2], the time will

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come when CLT buildings will be at the end of life. Most popular assumption of CLT service life is 50–60 years [1]. In addition, the CLT production step as it is today can be improved by increasing the circularity [5], [6].

To ensure effective material circularity, it is important to keep better record of used materials, recognize the volumes and types at the demolition phase, but the second step is the physical sorting, reuse, and recycling where necessary. Life cycle assessment (LCA) is a standard method for assessing the environmental impacts of a product in order to get an insight into impacts of specific stages of life. Life cycle impact research has shown that the biggest environmental impacts of CLT life cycle are created in the CLT production phase [6]. Cuttings from building preparation phase can be utilized to produce recycled CLT panels, if the practise would become a common practice, this would reduce the environmental impacts of virgin CLT panels, as waste would be reduced. Nevertheless, the technology for recycling has not yet reached the market to ensure sufficient recycling, the reCLT in Latvia is produced from post production cuttings of single-family dwelling housing unit [7].

Previous research on cross laminated timber (CLT) end of life (EoL) utilization shows that most life cycle impact categories have lower negative impacts of material recycling compared to utilization for energy recovery [7], the results showed how the recycling of cuttings can be beneficial to reduce environmental impacts of construction itself, as the residues are sent back to production phase, thereby replacing the virgin material needed to produce CLT. Using secondary raw material in larger volumes might result in lower overall environmental impacts. Previously described technology for CLT recycling [7] was based on the recycling of excellent quality cuttings, but the future of CLT recycling will require technologies dealing with used CLT recycling. After CLT have been exposed to humid condition, its structure is compromised by fungi attacks and hygrothermal processes (see Fig. 1.) [8].

The damaged layers might need to be replaced with new material in order to ensure material quality. Therefore, new technology has been proposed for dealing with CLT panels with damaged outer layers. Before resawing, rip- and cross-cutting to required dimensions, the outer layer is removed for the panel to be further used as a raw material for recycled CLT (ReCLT) production, avoiding the impacts from core layer production. Additionally, the use of existing waste stream wood increases the biogenic carbon storage in the economy [1,9]. To better understand the midterm and long term life cycle impacts of CLT and reCLT, comparative assessment of midpoint and endpoint should be made.

The midpoint method indicates the impact earlier in the cause-effect chain, while the endpoint indicates the final outcome. For example, when looking at toxic chemicals, the environmental impact of chemical spills needs to be taken into account. In such a case, the midpoint factors indicates an increase in the concentration of the chemical in water bodies, while the endpoint factors indicates the extinction of aquatic animals due to pollution [10]. The ReCiPe method provides 18 categories at the midpoint level that characterize the environmental impact of the system under study. These are then multiplied by damage factors and aggregated into three endpoint categories - damage to human health, damage to ecosystems and damage to resources [2].

The environmental impacts of building materials are becoming more important as companies have started to account their carbon emissions in more detailed manner according to GHG Protocol developed by the World Business Council for Sustainable Development and World Resources Institute. Under the Scope 3 companies are reporting their supplier emissions from the goods purchased, this includes all the construction materials used for the business [11]. This gives an advantage to companies that can provide equivalent products with lower emissions. It has been shown that using circular business models (CBM), the overall life cycle impacts of a wood products can be reduced [6]. Therefore, this study aims to assess the mid-point and end-point impacts of improved reCLT and CLT. By comparing the two products' impacts on global warming, human toxicity, water consumption, land use change, and many more, we are able to evaluate the benefits of increased CLT circularity in Latvia.

Fig. 1. Visual example of CLT panels with damaged surface planes. (pictures provided by Ltd. Forma).

2

2. Methodology

2.1. Case study location

The demonstration of improved CLT recycling was done by Ldt. "FORMA" engineers on the Ieriķi, Latvia premise. Ldt. "FORMA" is a SME providing custom machinery to woodworking industry in Latvia. This demonstration was carried out on a semi-industrial scale, processing one to three panels at a time. All the energy consumed for the processes were measured and included in the life cycle inventory (LCI) (see Annex 1).

2.2. Life cycle assessment

Life cycle assessment is a well-established tool used to assess the environmental impacts of all life cycle activities. It is used to quantify the environmental impact of a product or process. The International Organisation for Standardisation (ISO 14040) specifies that an LCA study should follow a framework consisting of four interrelated steps: goal and scope, LCI, life cycle impact assessment (LCIA) and interpretation [12].

The analysis starts by defining the objective of the study, functional unit (FU), system boundaries, assumptions and limitations, allocation and the chosen LCIA method in the Goal and Scope section. An LCI is then developed that includes input flows of water, energy and materials, and outputs including waste streams and releases to air, water and land. In the LCIA part, impact categories, category indicators and characterisation models are selected. Alongside all processes, the interpretation process assesses the completeness, sensitivity and consistency of the analysis and identifies conclusions, limitations and recommendations.

2.2.1. Goal and scope

The objective of the LCA is to determine the environmental impact of a recycled CLT panel made and to compare it with the environmental impact of a conventionally produced CLT panel. For this study, the functional unit was defined as 1 m^3 of cross laminated timber panels.

LCA was performed according to ISO 14040/14044 standards. SimaPro software was used for the analysis. Input datasets were taken from the Ecoinvent 3.8 database. ReCiPe Midpoint (H) life cycle impact assessment method was selected. No impact allocation was made in the study. A gate-to-gate LCA was carried out. Beyond the technical boundaries was the extraction of resources, transportation of resources, energy extraction, packaging material production and production of machinery.

2.2.1.1. ReCLT production processes.
In total, the processing of CLT cuttings consists of six steps: thickness splitting, formatting, tapping, first gluing and pressing, second gluing and pressing and packaging (see Fig. 1).

A recycling process had already been developed, which was covered by Vamza *et al.* in the 2021 study [7], but the company discovered a flaw: reprocessed CLT panels are not comparable to newly produced ones because they have visually noticeable joints that reduce their use cases. To solve this problem and add the recyclability of thicker cuttings, the recycling process was modified. Improvements in the recycling technology include removing the outer layers before joining the CLT cuttings and then apply a new layer at the end to cover the joints. This recycling approach is expanding the use cased from post-production to recovered CLT, as the layers might be damaged after prolonged exploitation, thereby have reduced mechanical properties [13].

The new reprocessing process starts with the removal of outer layers from the incoming CLT cuttings. The removed planks enter the waste stream. The process of removing the outer layer uses electricity to separate the layer from the rest of the CLT panel. The specific electricity consumption is 0.044 kWh on removed meter (see. Table 1.). The outer layers are 20 mm thick. CLT is assumed to have an average density of 490 kg/m^3 [14].

Once the outer layers are removed, the CLT cuttings are further formatted to acquire straight lines and 90° corners, straightening the round corners made by CNC end mills. Formatting removes 6 cm around the perimeter. The formatting is carried out with an electric saw, which consumes 0.01 kWh/m electricity. Removed edges end up in the waste stream. Sawing also generates sawdust, which enters the waste stream. For every meter cut, 5 mm are lost. All the generated waste from these processes are further shipped to fuel pellet producers and excluded from this study. In a complete CMB the energy from burning these pellets could be used for timber kilns.

Once the required dimensions have been obtained, it is necessary to make sure that the panels can be connected to each other. This

Table 1
Energy consumption of recycling process.

Process	Electricity consumption
	kWh per running m
Specific electricity consumption of thickness splitting (up to 6 m width)	0.044
Specific electricity consumption of formatting	0.01
Specific electricity consumption of tapping	0.16
	kWh per pressing
Per first pressing	0.09
Per second pressing (full reCLT panel)	0.09

is achieved by a tapping process in which finger joints are cut out in the edges for further connection. A visual representation is given in I. Vamzas et al. study [7]. The outer perimeter of the finished ReCLT panel, 18 m, remains without finger joints. The process is also carried out with an electric saw that consumes 0.16 kWh/m. The depth of the cut is 54 mm. Taking into account the length of the taping and the thickness of the panel, the volume of finger joints is obtained. The same volume is lost in sawdust.

Next the cuttings are glued and pressed together. The final dimensions are a 3×6 m ReCLT panel. Melamine urea formaldehyde (MUF) adhesive is used to join the finger-joint edges. The MUF glue ratio is 50:50 with hardener, application methodology included covering one surface of the finger-joint with the MUF glue and the other finger-joint surface with the hardener, thereby ensuring the hardening process takes place only when the parts are pressed together. The adhesive consumption is 0.3 kg per m^2 of joint surface. The joint surface is 0.58 m^2/m. After glue application, the panels are pressed with a hydraulic press that consumes 0.09 kWh per pressing. On average, three finished cuts can be pressed at the same time.

The second gluing and pressing is the application of the new outer layers. The surface layer is made of softwood planks with dimensions of 480 cm, 17 cm and 2 cm. Polyurethane (PUR) adhesive is used to fix the top layer and then it is pressed again to produce the final product. The consumption of PUR adhesive is 0.15 kg/m^2.

The final process is the packaging of the finished product. Packaging is done manually, so there is no electricity consumption. Also, it is assumed that there is no waste from packaging process, as trimmings from previous process steps are used in the packaging process. On each 50 m^3 of new product (reCLT), 1 m^3 of cuttings from previous processes are used.

The packaging is not depicted in Fig. 2, as there are no improvements or major differences comparing to standard practices. The system boundaries for LCA are indicated by the dashed line (see Fig. 3.). In the case study, company Ltd. "FORMA" provided data on the processing/manufacturing process. It should be noted that it is a pilot case for improved CLT recycling.

Post-production CLT cuttings are the main incoming material flow for the reCLT. The material comes in a range of size and thicknesses. They are sorted by usable area and thickness. Incoming material first is sorted based on the shape - complex geometric shapes are separated, leaving those with a reusable surface area greater than 1 m^2. The improved CLT recycling machinery is suitable for incoming material of CLT cuttings with thickness of 80, 100, 120, 140, 150, 160, and 200 mm. For this analysis, cuttings with thickness of 80–120 mm were excluded, as their recycling do not require thickness splitting and the smaller thickness cutting recycling is described in previous publication [7]. Cuttings are sourced from three different CLT production plants in Latvia (Cross Timber Systems, Nordic CLT) and Estonia (Arkwood) and processed in Ltd. Dārdu street 3, Ieriķi, Latvia. The average driving distance is 163 km. When the CLT cuttings are delivered to the reprocessing site, all the processes take place in one location, reducing the further transportation needs.

2.2.1.2. Assumptions and limitations. This section will highlight the modeling assumptions when selecting built-in materials or processes from the Ecoinvent database. Recycling is described in more detail as data on the production of new CLT was not available from the company.

Unit datasets were used throughout, rather than system datasets. All inputs were taken from the market as indicated at the system
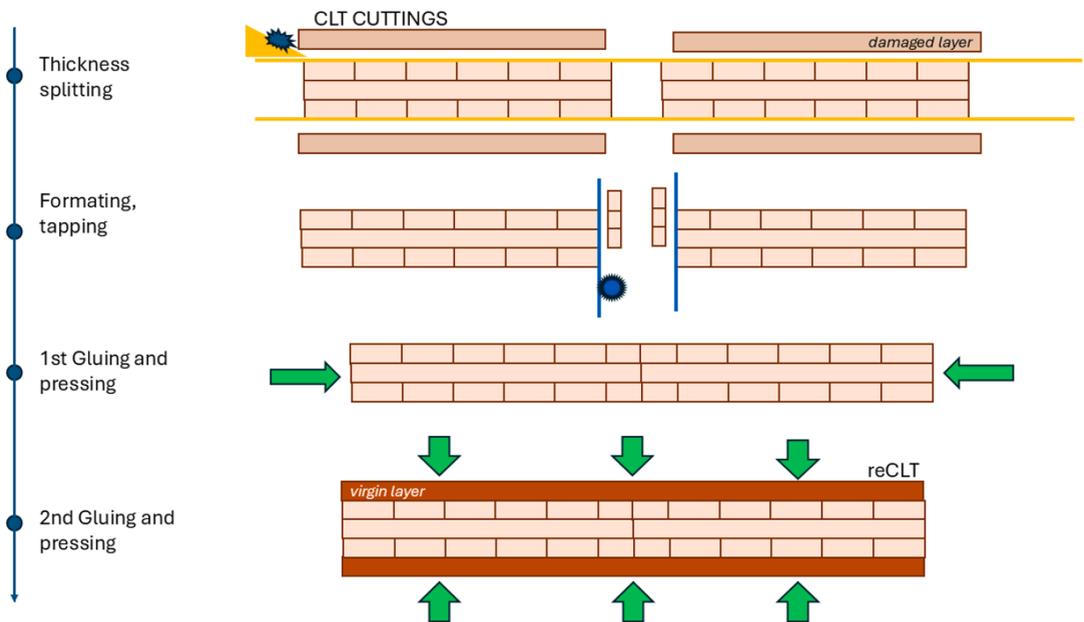

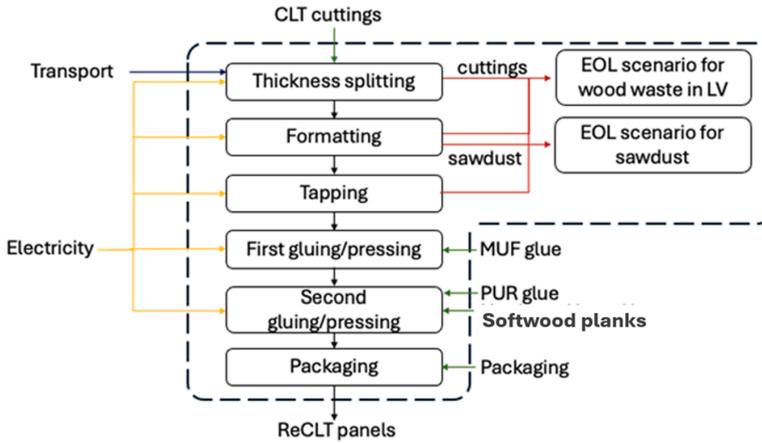**Fig. 2.** Visual diagram of the improved recycling process.

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Fig. 3. Flow chart of CLT production from CLT cuttings with system boundaries.

boundaries as the production of inputs were not analysed in detail. For this demonstration and LCIA only post-production CLT cuttings were used, although it is expected to test the recycling technology on post-consumer CLT panels (see Fig. 1.) in the coming future. The CLT cuttings entering the recycling process are environmental burden-free as they were not produced for the purpose of reCLT production, therefore the environmental impacts are already accounted in the CLT production. For the recycling process, all processes were built from scratch using the built-in material flows.

The location for materials and processes was chosen in priority order - Latvia, Europe, Global. The transport was used only for the transport of the CLT cutting and was taken as *transport, freight, lorry 16–32 metric ton, EURO5*. Latvian grid data was used for electricity in all processes - *market for electricity, medium voltage*. The medium voltage was chosen because it was used in the built-in cross laminated timber production dataset, so we assumed the same.

Two types of adhesives - melamine urea formaldehyde and polyurethane - were used in the production of ReCLT and new CLT, both of which were taken from the Ecoinvent database under the same name. ReCLT production involves the application of a new outer layer, which is softwood, so dataset *sawn wood, board, softwood, dried (u=10 %), planned* was taken.

Two types of waste are generated in the production of ReCLT: sawdust and cuttings. The cuttings have the properties of CLT, but the closest waste type that could be used for modelling was chosen. The waste type selected was *waste wood, untreated* built-in. Its disposal scenario was a Latvian case with 3 % open burning, 15 % open dumping, 4 % unsanitary dumping, 77 % sanitary dumping [15]. The second type of waste is sawdust, which was treated as built-in waste type *sawdust, loose, wet, measured as dry mass*. In the analysis sawdust built-in waste scenario is used [16], nevertheless, in most cases company ensures to transfer the waste to solid fuel pellet producers. Therefore, this scenario includes the collection and storage of sawdust but does not include what happens to it at the end, whether it is landfilled, incinerated or otherwise, as this might change. This was done because the environmental impact of this process is minor in the overall assessment.

As a packaging material for each 1 m^3 of product, 0.02 m^3 of CLT cutting were used as a spacers for reCLT panels.

CLT recycling company does not produce virgin CLT, therefore, a literature review was carried out to find life cycle inventory for CLT production. Chosen Environmental product declaration represented virgin CLT production in Latvia, thereby providing comparative data for the comparison.

A review of several product environmental declarations revealed that data on electricity consumption and waste were missing or aggregated over several life cycle stages, some of which are not included in this study [17,18,19]. This was most likely due to data protection concerns. A complete life cycle inventory of CLT production comparable to our case was not available in the scientific literature. It was therefore decided to use the built-in Ecoinvent process as it reflects the average situation in Europe [20].

SimaPro built-in process was modified - *cross laminated timber production* - to the boundaries of our study and to fit Latvia's case. Original data in dataset are based on a sample of CLT production in Germany [20]. The first big distinction was the boundaries of the system, because the process includes the production of machinery, which was taken out because it did not fit the boundaries of present study. Next, synthetic rubber was taken out, as it is not used in the case of Latvia. Lubricating oils needed to maintain the equipment were included in the process. In our situation, given the low production capacity, this was also removed. Waste streams associated with the removed input streams were removed.

Additional reasoning for machinery removal was different scales of CLT and reCLT production, as reCLT production is only pilot scale, adequate machinery comparison will be possible after scaling the reCLT production to at least TRL9.

Gathered life cycle inventory (LCI) of FU (m^3) CLT and reCLT is shown in Annex 1.

3. Results

3.1. Midpoint and endpoint impact of ReCLT

Regarding reCLT, the largest impacts in most categories are both gluing processes. In both processes petrochemical adhesives are used. The process with the third largest impact is the thickness splitting, showing greatest impact on freshwater eutrophication and marine eutrophication. As this process consumes the most energy per FU. Impacts in land use category show that almost all the reCLT impacts are due to second gluing and pressing (see Fig. 4.), this is due to the use of virgin material, as for this case study primary raw material was sourced for the outer layer production, ensuring identical visual quality with the CLT.

For the endpoint impacts (see Fig. 5.), using ReCiPe methodology, three categories were assessed – human health, ecosystem, and resources. Analysis showed that human health category had the greatest impact by single score resulting in 3.68 Pt. Again, the gluing processes accounted for more than half of the impact, with thickness splitting in third place. In the ecosystem impact category, the second gluing with PUR glue showed the largest impact, accounting for half of the total. The resource category showed the lowest impact, as the process does not use any rare elements and most of the FU is made of renewable material.

3.2. Comparison of midpoint and endpoint impacts of ReCLT and CLT

To truly evaluate the benefits of using recycling technology, the reCLT was compared with CLT using the midpoint and endpoint indicators showing the impact of each product, allowing for the side-by-side comparison. For the midpoint comparison (see Fig. 5.) almost all impact categories show smaller impacts for the reCLT's FU. Only exception where the reCLT shows larger negative impacts are eutrophication categories resulting in 0.48 kg of phosphorous equivalent for the freshwater eutrophication and 0.36 kg of nitrogen equivalent. These impacts have been linked with inappropriate disposal of biomass residues [6], therefore some of the impacts in the case study could be linked to disposal of sawdust. Most notable improvements are in the global warming, land use, and terrestrial ecotoxicity impact categories (see Table 2).
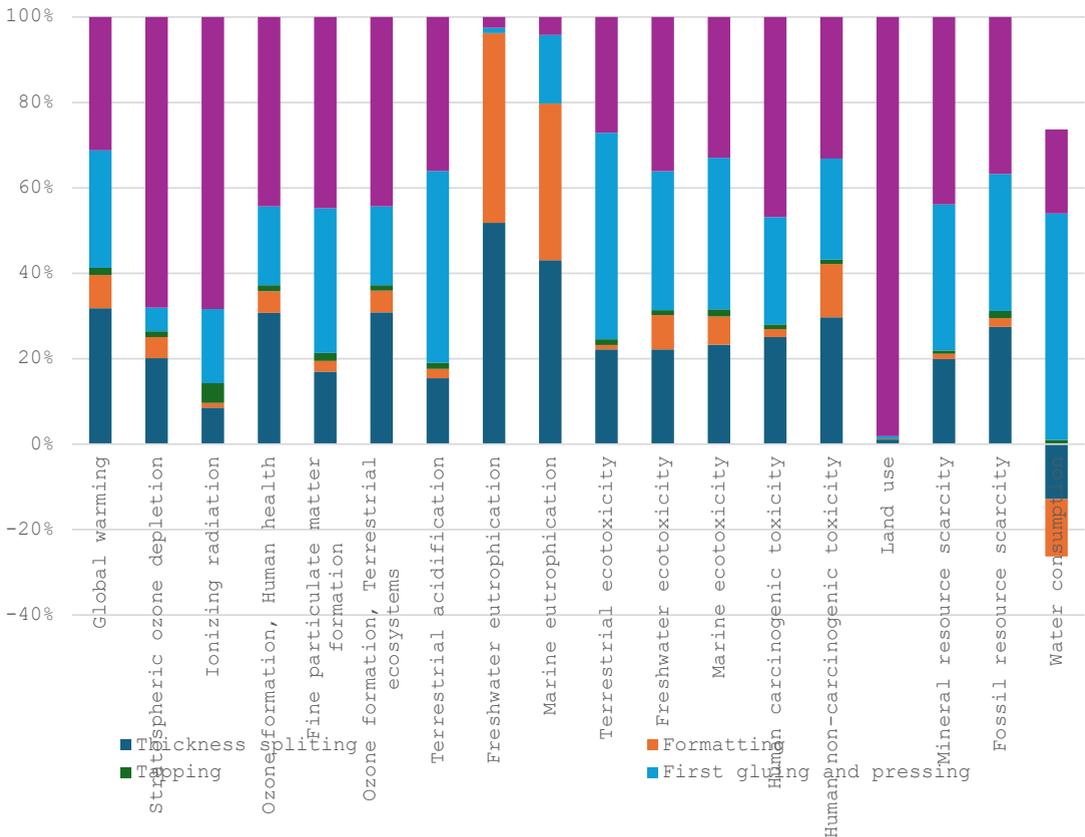
Fig. 4. Potential midpoint impacts of 1 m³ recycled cross-laminated timber.
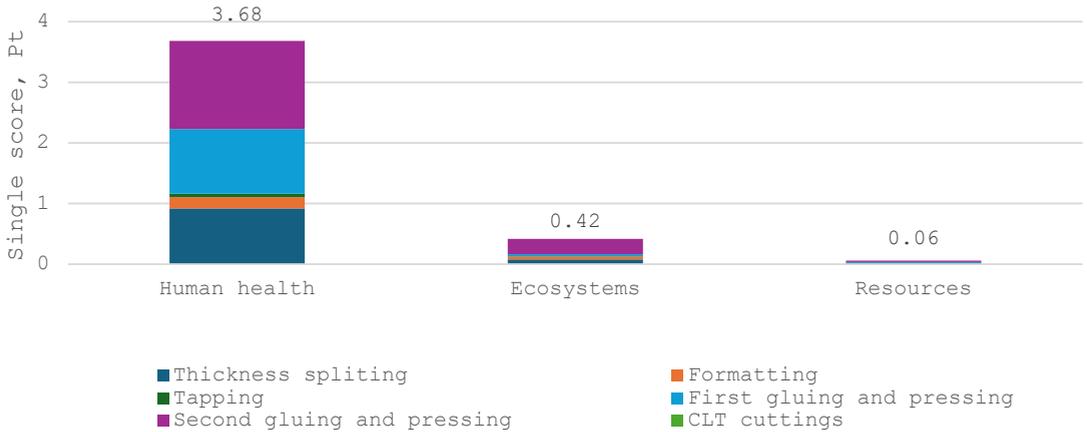
Fig. 5. Endpoint single score impacts of 1 m^3 of recycled cross-laminated timber.

Table 2
Potential midpoint impacts of 1 m^3 of recycled cross-laminated timber (reCLT) and cross laminated timber.

Impact category	Unit	ReCLT	CLT
Global warming	kg CO$_2$ eq	82.76	151.24
Stratospheric ozone depletion	kg CFC11 eq	0.00006	0.00017
Ionizing radiation	kBq Co−60 eq	3.96	16.73
Ozone formation, Human health	kg NO$_x$ eq	0.23	0.87
Fine particulate matter formation	kg PM2.5 eq	0.11	0.38
Ozone formation, Terrestrial ecosystems	kg NO$_x$ eq	0.24	0.92
Terrestrial acidification	kg SO$_2$ eq	0.26	0.56
Freshwater eutrophication	kg P eq	0.54	0.06
Marine eutrophication	kg N eq	0.049	0.013
Terrestrial ecotoxicity	kg 1,4-DCB	2302.88	4243.63
Freshwater ecotoxicity	kg 1,4-DCB	3.80	6.11
Marine ecotoxicity	kg 1,4-DCB	6.82	12.93
Human carcinogenic toxicity	kg 1,4-DCB	15.35	36.44
Human non-carcinogenic toxicity	kg 1,4-DCB	94.98	153.25
Land use	m^{2}a crop eq	94.08	861.79
Mineral resource scarcity	kg Cu eq	0.26	0.48
Fossil resource scarcity	kg oil eq	23.33	46.78
Water consumption	m^3	0.63	1.81

ReCLT shows more considerable negative impacts un the Freshwater and Marine Eutrophication categories, this can be due to chosen ammonium sulphate hardener in the gluing process. Relative impact comparison in the midpoint is depicted in Fig. 6, showing the proportional gains of reCLT, especially in the land use category.

Aggregated impact comparison is shown by the endpoint using the single score (see Fig. 6.), again showing the reCLT accumulates in smaller negative impacts compared to CLT with almost 60 % reduction on human health and more than 80 % on the ecosystem, with the smallest decrease being 50 % on the resources category.

4. Discussion and conclusions

Life cycle analysis of the case study shows that even the use of virgin material for improved visual quality of the reCLT, recycling route is overall more beneficial compared to CLT production purely from virgin timber.

Environmental benefits of recycling CLT reach out further than purely product vs. product comparison. Extensive studies have shown that recycling of the retrieved CLT after demolition improve the overall building environmental footprint adding prolonged biogenic carbon storage in products [1]. Although global warming impacts showed ReCLT superiority compared to CLT, mechanical properties were not tested in the scope of this research, previously done research show compatible mechanical properties for single-family dwelling' construction [7]. Largest environmental gains are attributable to land use, as in the case of ReCLT there is reduced need for virgin timber. Although in the case study, virgin material is used, the planks for outer layer could be replaced with retrieved sawnwood instead of primary sawnwood, thereby increasing the timber cascade [9] and reducing the impact on land use.

Overall, largest negative impacts of the ReCLT were attributed to the used adhesives. Both MUF and PUR are known for their
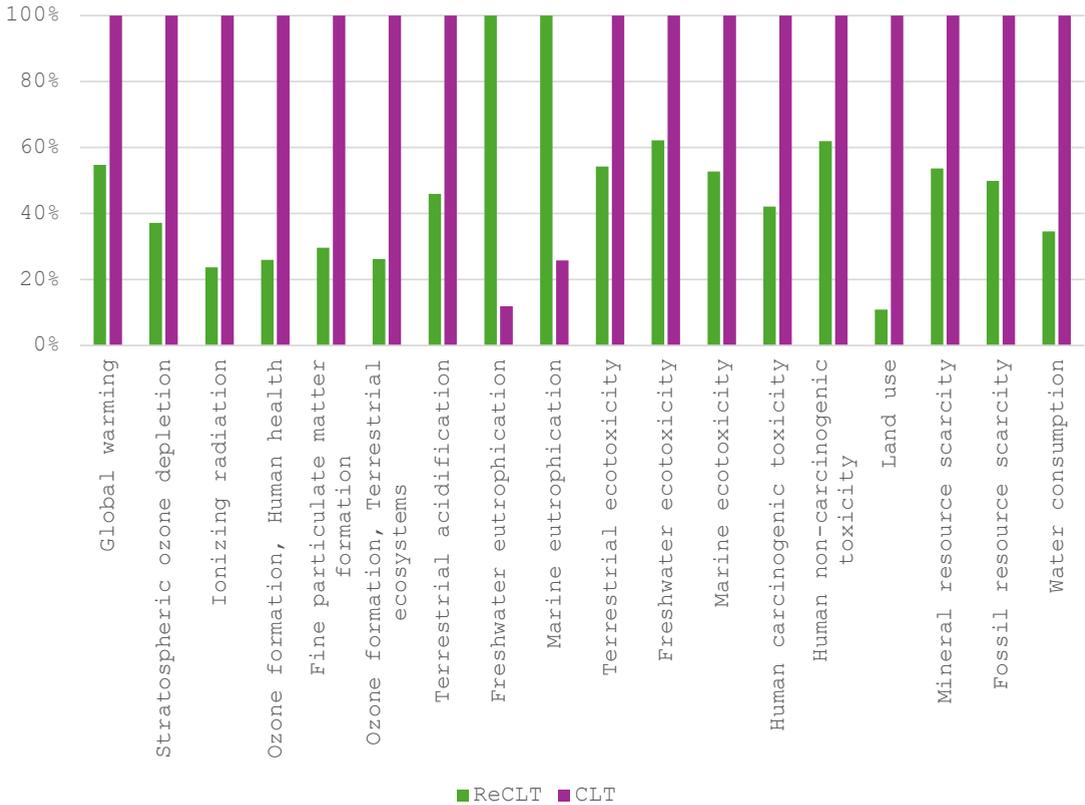
Fig. 6. Potential midpoint impacts of 1 m^3 recycled cross-laminated timber (reCLT) and cross laminated timber (CLT).
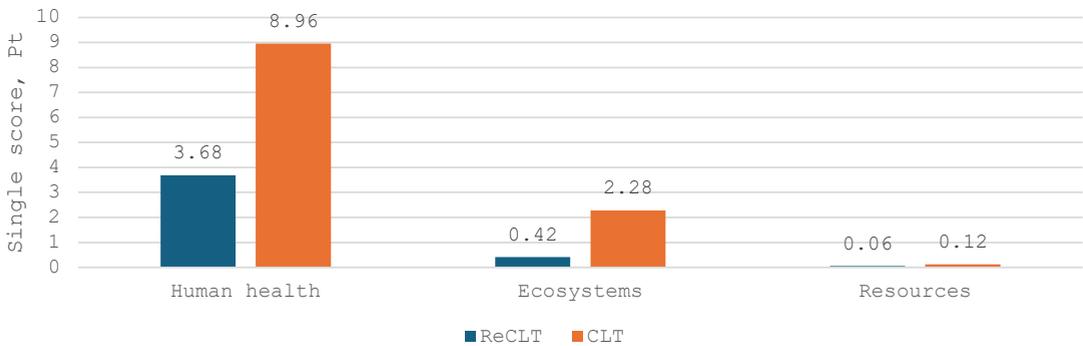

Fig. 7. Endpoint single score impacts of recycled cross-laminated timber (reCLT) and cross-laminated timber (CLT).

negative effects, therefore replacement of these adhesives with lignin-based adhesives in the final product can benefit the ReCLT performance in LCA calculation. The negative effects of ecotoxicity could be reduced if all the sawdust and cuttings would be disposed in more efficient manner and energy mix from the Latvia's grid could be replaced by energy with larger renewable energy contents, at this point the renewable energy in Latvia's mix accounts for maximum of 43 % [6]. Previous research on CLT unrecyclable residues have shown that incineration is not the most preferable option [5], and from the cascade perspective as well, the residues could be incorporated into other products with longer lifespan [6].

In conclusion, with the existing recycling technology, the produced ReCLT is overall preferable form life cycle perspective,

nevertheless, there are some improvements that could improve the ReCLT performance, e.g., transition to renewable energy, green lignin-based adhesives, and post-consumer wood for the outer layer replacement. Additionally, more comprehensive LCA could be updated when the recycling technology TRL will be increased to 9 or higher, ensuring the inclusion of full-scale production line's machinery.

CRediT authorship contribution statement

Dagnija Blumberga: Writing – review & editing, Supervision. **Peteris Vasuks:** Resources, Data curation. **Ilze Vamza:** Writing – original draft, Validation. **Tereza Bezrucko:** Validation, Investigation. **Megija Valtere:** Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peteris Vasuks reports financial support was provided by Forest Sector Competence Centre of Latvia. Peteris Vasuks reports a relationship with Panacea Biotec Ltd Vaccine Formulation Plant Lalru that includes: board membership. There are no other conflict of interests for the rest of the authors: Ilze Vamza, Megija Valtere, Tereza Bezrucko, and Dagnija Blumberga. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Annexes

Table A1
Inventory of the recycled cross laminated timber (reCLT)

Process - ReCLT production	Amount	Unit	Location
PRODUCT			
ReCLT	1.00	m^3	n/a
INPUTS			
Material/transport			
CLT cuttings	1.20	m^3	n/a
Land transport, freight, lorry 16–32 metric ton, EURO5	95.86	tkm	Europe
Polyurethane adhesive	2.35	kg	Global
Melamine urea formaldehyde adhesive	5.22	kg	Global
Ammonium sulfate (hardener)	5.22	kg	Europe
Sawnwood, board, softwood, dried (u=10 %), planed	0.12	m^3	Europe
Electricity/heat			
Electricity, medium voltage,	2.68	kWh	Latvia
OUTPUTS			
Waste to treatment			
Cuttings (waste wood, untreted)	136.74	kg	Latvia
Sawdust	29.91	kg	Global

Table A2
Table A Inventory of cross laminated timber (CLT)

Process - CLT production	Amount	Unit	Location
PRODUCT			
CLT	1	m^3	n/a
INPUTS			
Material/transport			
Sawnwood, board, softwood, raw, dried (u=10 %)	0,88	m^3	Europe
Ammonium sulfate (hardener)	0.02	kg	Europe
Melamine urea formaldehyde adhesive	3,67	kg	Global
Polyurethane adhesive	3,29	kg	Global
Sawlog and veneer log, softwood, measured as solid wood under bark	0,58	m^3	Europe

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Table A2 (*continued*)

Process - CLT production	Amount	Unit	Location
Tap water	81,96	kg	Europe
Electricity/heat			
Electricity, medium voltage,	93,74	kWh	Latvia
Diesel, burned in building machine	71.04	MJ	Global
Furnace, wood chips, with silo, 300 kW	1.34	p	Global
OUTPUTS			
Waste to treatment			
Municipal solid waste	0,40	kg	Latvia
Wastewater from particleboard production	0,11	m^3	Global
wood ash mixture, pure	0,39	kg	Europe
Emissions to air/water			
Acetaldehyde	4,7E−05	kg	n/a
Acetone	1,6E−01	kg	n/a
Ammonia	1,3E−03	kg	n/a
Arsenic	7,8E−07	kg	n/a
Benzene	7,1E−04	kg	n/a
Benzene, ethyl-	2,3E−05	kg	n/a
Benzene, hexachloro-	5,6E−12	kg	n/a
Benzo(a)pyrene	3,9E−07	kg	n/a
Bromine	4,7E−05	kg	n/a
Cadmium	5,4E−07	kg	n/a
Calcium	4,6E−03	kg	n/a
Carbon dioxide, non-fossil	8,3E+ 01	kg	n/a
Carbon monoxide, non-fossil	3,9E−01	kg	n/a
Chlorine	1,4E−04	kg	n/a
Chromium	3,1E−06	kg	n/a
Chromium VI	3,1E−08	kg	n/a
Copper	1,7E−05	kg	n/a
Dinitrogen monoxide	1,9E−03	kg	n/a
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2,4E−11	kg	n/a
Fluorine	3,9E−05	kg	n/a
Formaldehyde	5,6E−03	kg	n/a
Hydrocarbons, aliphatic, alkanes, unspecified	7,1E−04	kg	n/a
Hydrocarbons, aliphatic, unsaturated	2,4E−03	kg	n/a
Lead	1,9E−05	kg	n/a
m-Xylene	9,3E−05	kg	n/a
Magnesium	2,8E−04	kg	n/a
Manganese	1,3E−04	kg	n/a
Mercury	2,3E−07	kg	n/a
Methane, non-fossil	3,5E−03	kg	n/a
Nickel	4,7E−06	kg	n/a
Nitrogen oxides	1,4E−01	kg	n/a
NMVOC, non-methane volatile organic compounds, unspecified origin	5,4E−03	kg	n/a
PAH, polycyclic aromatic hydrocarbons	8,6E−06	kg	n/a
Particulates, < 2.5 μm	7,0E−02	kg	n/a
Particulates, > 2.5 μm, and < 10um	7,0E−02	kg	n/a
Phenol, pentachloro-	6,3E−09	kg	n/a
Phosphorus	2,3E−04	kg	n/a
Potassium	1,8E−02	kg	n/a
Sodium	1,0E−03	kg	n/a
Sulfur dioxide	1,9E−03	kg	n/a
Toluene	2,3E−04	kg	n/a
Water	1,4E−01	m^3	n/a
Zinc	2,3E−04	kg	n/a

Data Availability

The authors do not have permission to share data.

References

[1] A. Younis, A. Dodoo, Cross-laminated timber for building construction: a life-cycle-assessment overview, J. Build. Eng. 52 (2022) 104482, https://doi.org/10.1016/j.jobe.2022.104482.

[2] Maria Fernanda Laguarda Mallo and Omar Espinoza, Cross-Laminated Timber Vs. Concrete/Steel: Cost Comparison Using A Case Study, presented at the WCTE2016 World Conference on Timber Engineering, Vienna, Austria, 2017.

[3] T. Singh, et al., Emerging technologies for the development of wood products towards extended carbon storage and CO2 capture, Carbon Capture Sci. Technol. 4 (2022) 100057, https://doi.org/10.1016/j.ccst.2022.100057.

[4] A. Jayalath, S. Navaratnam, T. Ngo, P. Mendis, N. Hewson, L. Aye, Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia, Energy Build. 223 (2020) 110091, https://doi.org/10.1016/j.enbuild.2020.110091.

[5] I. Vamza, K. Valters, I. Luksta, P. Resnais, D. Blumberga, Complete circularity in cross-laminated timber production, Environ. Clim. Technol. 25 (1) (2021) 1101–1113, https://doi.org/10.2478/rtuect-2021-0083.

[6] C.K. De Carvalho Araújo, et al., Life cycle assessment as a guide for designing circular business models in the wood panel industry: a critical review, J. Clean. Prod. 355 (2022) 131729, https://doi.org/10.1016/j.jclepro.2022.131729.

[7] I. Vamza, F. Diaz, P. Resnais, A. Radziņa, D. Blumberga, Life cycle assessment of reprocessed cross laminated timber in Latvia, Environ. Clim. Technol. 25 (1) (2021) 58–70, https://doi.org/10.2478/rtuect-2021-0005.

[8] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development, Eur. J. Wood Wood Prod. 74 (3) (2016) 331–351, https://doi.org/10.1007/s00107-015-0999-5.

[9] A. Hafner, S. Ott, S. Winter, Recycling and End-of-Life Scenarios for Timber Structures, in: S. Aicher, H.-W. Reinhardt, H. Garrecht (Eds.), Materials and Joints in Timber Structures, Springer Netherlands, Dordrecht, 2014, pp. 89–98, https://doi.org/10.1007/978-94-007-7811-5_8.

[10] Making LCA results count, PRé Sustainability. (Accessed: Nov. 25, 2024)Available: https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/.

[11] J. Ranganathan, Laurent Corbier, Pankaj Bhatia, Simon Schmitz, Peter Gage, Kjell Oren, Greenh. Gas. Protoc.: A Corp. Account. Report. Stand. (2004).

[12] 2006 Environmental Management - Life Cycle Assessment - Principles and Framework, 14040, Geneva, Switzerland., 2006. [Online]. Available: ⟨https://www.iso.org/standard/37456.html⟩.

[13] E.L. Schmidt, M. Riggio, A.R. Barbosa, I. Mugabo, Environmental response of a CLT floor panel: lessons for moisture management and monitoring of mass timber buildings, Build. Environ. 148 (2019) 609–622, https://doi.org/10.1016/j.buildenv.2018.11.038.

[14] M. Wieruszewski, B. Mazela, Cross laminated timber (CLT) as an alternative form of construction wood, Drv. Ind. 68 (4) (2017) 359–367, https://doi.org/10.5552/drind.2017.1728.

[15] Ecoinvent, waste wood, untreated

[16] Ecoinvent, sawdust, loose, wet, measured as dry mass

[17] Stora Enso, 2021KVH ® structural timber, EPD S-P-02153,Available: ⟨https://www.storaenso.com/-/media/documents/download-center/certificates/wood-products-approvals-and-certificates/epd/stora-enso-epd-kvh-2021.pdf⟩.

[18] Timberlink Australia Pty Ltd, Cross laminated timber (CLT) glue laminated timber (GLT), EPD EPD-IES-0007432:002 (S-P-07432), 2019. [Online]. Available: ⟨https://www.environdec.com/library/epd7432⟩.

[19] Financiera Maderera S.A., CLT (Cross Laminated Timber), EPD EPD-IES-0010735:002 (S-P-10735), 2019. [Online]. Available: ⟨https://www.environdec.com/library/epd10735⟩.

[20] Ecoinvent, cross laminated timber production.

Uncertainty of Life Cycle Assessment Studies for Blended Textiles

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Abstract – **Textile fibres are derived from natural and artificial fibres and, in some cases, are blended together to ensure optimum properties. Textiles made from cotton and polyester blends currently hold a significant market share as they are relatively inexpensive, offer excellent performance, and have complementary properties. However, the production and consumption of textiles contribute significantly to environmental degradation and greenhouse gas emissions, but the scale of the impact is uncertain and under debate. This is also the case in studies of cotton and polyester blends, as a detailed life cycle inventory of the production of this material is absent in the scientific literature, thus affecting its environmental impact assessment. Therefore, the study aimed to identify the limitations and assumptions used so far in the environmental assessments of cotton and polyester blends and to assess the uncertainties they may introduce in future environmental assessments. Two methods were used: literature analysis and scenario-based life cycle assessment. The literature analysis summarized five studies and reports that have carried out an environmental assessment of blended textiles and provided inventory data. The results of the life cycle assessment showed that it is not possible to fill the knowledge gap by creating a new life cycle inventory using existing literature data. This is because the uncertainty in results was too high, reaching as much as 772 % difference from the baseline scenario. Nevertheless, this study is a step towards a complete life cycle inventory and can improve the future environmental assessment of textile blends.**

Keywords – **Cotton; environmental impact; fabric; Life Cycle Inventory (LCI); literature analysis; mixed fibre; polyester.**

1. INTRODUCTION

The textile industry has a significant environmental impact due to resource-intensive production and high demand for textile products [1]. In the European Union, textiles are the third largest category regarding land and water use and the fourth largest category regarding negative environmental impact and climate change [2]. This impact will only increase as consumption is expected to grow rapidly under the current business-as-usual approach. The production of textiles is the most impactful part of their life cycle, as it consumes large amounts of energy, water, and chemicals [3], [4]. Overall, these impacts can account for almost 70 % of the total life cycle environmental impacts – fibre production (38 %), yarn

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production (8 %), fabric production (6 %), and wet processing (15 %) [5]. However, this depends on the fibre type, processing methods, and technologies.

Textile production and finishing include a variety of technological phases, depending on the desired properties and specific use case of the final product. The basis for the properties is ensured by various types of fibres – man-made, natural, and artificial which offers different properties and often multiple types of fibres are combined to achieved desired properties for the final product [6]. The most commonly used natural fibre for textile production is cotton, making up 23 % of all fibres produced globally [7]. Cotton production has significant negative environmental and social impacts despite its natural origin. These impacts are caused by the intensive use of land, water, pesticides, and chemicals in the production process [8].

Man-made fibres can be classified by their polymeric origin: natural and synthetic polymers [8]. Polyester is the most widely used synthetic fibre, accounting for 52 % of textile fibres [7]. Environmental concerns are mainly linked to dependence on fossil resources for materials and energy [9]. In the production of polyester textiles, harmful chemicals and dyes are also often derived from fossil resources. Another issue with synthetic textiles is the creation of microplastics during their use and at the end of their life cycle [10].

Blended textiles are commonly used because blending two or more fibre types gives combined and unique characteristics [6]. The most common blended textile on the market is cotton/polyester (CO/PES), used in different proportions. This blend is so popular and widely used in everyday clothing as polyester provides durability, anti-wrinkle properties, fast drying, and shape retention, while cotton offers comfort, moisture control, and breathability of fabric [11]. However, once a blended textile reaches the end of its life cycle, significant challenges arise because the various blends and complex structures make recycling complicated [6], [12]. Cotton and polyester blends are no exception. Moreover, the different percentages of blends prevent a standardized system for their separation and recycling.

The most widely applied method to evaluate the environmental impact of a product is the life cycle assessment (LCA) [13]. The analysis can cover the entire life cycle, from raw material extraction to the end of the life cycle, such as disposal or recycling. The LCA method is also used to evaluate textiles. Numerous LCA studies have been performed to assess textiles, taking into account variables such as fibre, processing methods, and the type of textile product manufactured [14]–[16]. Also, some studies focus specifically on a particular stage of the life cycle, for example, wet processing [17] recycling and reuse [18]

When performing an LCA, uncertainty is one of the main factors affecting the reliability of the LCA results [19]. Uncertainty in LCA arises in several ways and can be divided into nine classes [20]. The most commonly measured and considered type of uncertainty is the parameter uncertainty which includes variability and uncertainty in model input parameters. The two most widely used methods for quantifying uncertainties in this area are the Monte Carlo simulation and sensitivity analysis [19]. Monte Carlo simulation is a numerical propagation of uncertainty that operates by generating random samples for all input variables, inserting these values into the model to obtain results, and analysing the impact on the results [20]. Sensitivity analysis has many definitions and is used in various ways. It can be used in the same way as the previous method, by changing numerical inputs or by changing specific system characteristics [20]. If a system characteristic or set of parameters is changed, a scenario analysis is performed where different scenarios are run and compared with each other. Scenario analysis can be considered as a form of sensitivity analysis [20].

A knowledge gap was identified when looking more closely at the LCA studies on CO/PES blends. Several studies have been carried out on the environmental impact of this material [13], [21]–[23], but they do not cover a detailed life cycle inventory (LCI). Wagner *et al*. also identified this knowledge gap [13]. A literature review is necessary to develop a complete

LCI for CO/PES blends. This will improve the understanding of what has been studied so far, what assumptions have been made in the LCA of blended textiles, and why a comprehensive LCI has not been developed. Therefore, the aim of this study is to review the literature on environmental assessment studies of cotton and polyester blend production and to identify what data assumptions have been made so far and to assess how these data variations can introduce uncertainties in environmental impact assessments using scenario-based life cycle assessment. Textile production and consumption are known to contribute to environmental degradation and greenhouse gas emissions, but the actual size of this impact is still unclear and under debate [4]. Thus, a step closer to a complete life cycle inventory can help assess textiles' environmental impact more accurately, leading to improved knowledge on their sustainability.

2. METHODOLOGY

When developing new technologies for recycling processes, their environmental impact needs to be assessed in comparison with existing technologies on the market [18]. Recycling technologies for textiles are currently under active research. In order to compare the environmental impact of blended textile recycling processes with that of virgin textile production, an environmental impact assessment is necessary. Thus, the final objective is to carry out a life cycle assessment of the production and recycling of the polyester and cotton blend. However, in order to do so, a complete LCI is needed. Hence, an algorithm was developed to understand the steps to be taken to reach the final goal (see Fig. 1).
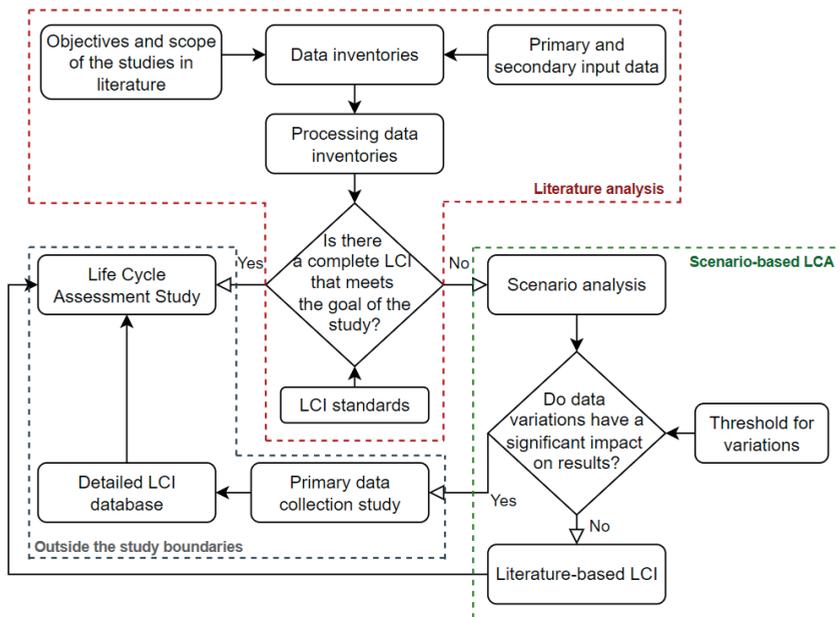
Fig. 1. Algorithm for the methodology.

Initially, a literature analysis should be carried out to obtain a complete LCI for blended textiles. To determine whether the LCI obtained from the literature is complete, the inventory standards for the specific product should be analysed. If a complete LCI is already available

in the literature, it can be used as the LCI base for the LCA study. Certainly, minor adaptations should be made to make it more suitable for the specific product under investigation. On the other hand, if a complete LCI is not available in the literature, further analysis will be needed to determine whether a complete LCI can be developed from the data available in the literature.

The aim of the further analysis is to investigate the impact on the life cycle assessment if the LCI were to be created from the inventories found in the literature. It is therefore necessary to choose a base inventory that is the most relevant to the scope of the study and the most complete inventory. The analysis can be carried out using Monte Carlo simulation or sensitivity analysis by varying a number of input parameters based on data found in the literature. In this case, several parameters would be changed separately and the impact on the system of a particular parameter would be measured. However, the parameters are interrelated, e.g., hydrogen peroxide and sodium hydroxide depend on each other [24], so this relationship would be ignored. It is therefore better to carry out a scenario analysis in which several parameters can be changed simultaneously.

Scenario analysis is most often used to develop and test future scenarios or best and worst case scenarios [20], for example future-oriented LCA with qualitative scenarios for agri-food sector [25], scenario-based LCA to evaluate future impacts of offshore wind [26] and scenario-based LCA for best and worst case end-of-life scenarios for renewable energy systems [27]. To our knowledge, the use of scenario-based LCA to test data variations and the resulting uncertainties has not been used so far. However, the methodology is suitable for such a study.

In scenario-based LCA each scenario will be based on the baseline scenario and the variable parameters will come from inventories found in the literature. The analysis will result in variations that will be compared to a threshold value to determine whether they are significant or not. If they are not significant, a LCI for the product will be created from the literature data. However, if significant, further research will be needed to obtain primary data to build a new LCI database for blended textiles.

2.1. Literature Analysis

The literature analysis started with a bibliometric analysis to gain an overview of the research area and to identify the main keywords for further use. Bibliometric analysis is a quantitative method used to assess the current state of a research field by looking at the interrelationships between scientific publications in that field [28]. The analysis is based on a large number of scientific publications, which are analysed using software that uses statistical and network tools. *VOSviewer* software was used in this study.

The aim was to gain insight into research on the environmental impact of blended textiles, particularly CO/PES blends. For bibliometric analysis, Scopus or Web of Science databases are recommended [29]. The Web of Science database was used in this study, as 381 results were found for the given keywords, while 211 results were found in the Scopus database. The keywords were combinations between environmental impact and environmental assessment and between mixed textiles, blended textiles, and cotton-polyester blends, for example, environmental impact mixed textiles. In total, six keywords were created and separated by "OR".

After the first analysis, a number of words were identified and changed in the original file as they had the same meaning but different spellings, e.g., LCA and life-cycle assessment were replaced by life cycle assessment. After that, a threshold was chosen. The number of keyword occurrences above 12 was selected because logical clusters were formed, and the number of words was not too high.

Using the identified keywords, further literature analysis was carried out to summarize studies on the environmental assessment of CO/PES blend production. To do this, keywords from the life cycle assessment cluster were used mainly, but occasionally, keywords from other clusters, like wastewater and toxicity, were used. In addition to the existing keywords, authors also searched for studies on specific stages of textile production – yarn sizing, weaving, pre-treatment, dyeing, and finishing. Three databases were used – Web of Science, Google Scholar, and Scopus. The studies were qualitatively assessed, and only those with sufficient quantitative data were selected for further analysis.

After the literature review, the *Ecoinvent* database was also explored as it will be used in further analysis. The database contains datasets on various sectors, such as energy production, transport, and materials. It contains more than 20 000 interlinked datasets [30]. Therefore, it was examined whether the database includes processes for the production of CO/PES blends.

Also, the Product Category Rules (PCR) were reviewed to get an idea of what a complete LCI should look like. PCRs have been developed for specific products or product groups to be followed when carrying out an LCA for an Environmental Product Declaration (EPD) [31]. They provide guidance on things like system boundaries, functional units and LCI. To determine the threshold of potential uncertainty, LCA standards [32]–[34] and methodology study [20] were reviewed.

2.2. Scenario-Based Life Cycle Assessment

LCA method was used to analyse the data from the literature review. The aim of the analysis was to evaluate the potential uncertainties on the environmental assessments of CO/PES blended textiles due to differences in available data and assumptions made in the literature. When comparing scenarios against each other, it is not the value of the impact score that matters, but the difference or ratio between the impact scores. Thus, absolute values are irrelevant when assessing uncertainty [20]. The results of the LCA scenarios will therefore be presented as ratios. It is important to note that each study on which the scenarios are based has different inputs and processes with various technologies. It is also one of the sources of uncertainty in LCA. The literature review shows that studies often use data from the literature that are close to the target but do not come from exactly the same technological processes as the specific case [13], [23]. This is done in the absence of specific data. Therefore, the current analysis does not take into account the variety of technologies in order to consider their impact on uncertainty.

The scope of the LCA was based on the study on which the baseline scenario is based [13]. The functional unit in the reviewed study is woven doctor's trousers (unisex) in white with two side pockets and two back pockets with material parameters cotton-polyester yarn (35/65), 470 dtex [13]. However, the material parameters are only relevant at the beginning of yarn production, as all other production processes have been adopted from cotton production [35]. In the current study, only fabric production is considered, so the functional unit is 1 kg of cotton and polyester blended textile with the same material parameters. The unit of weight was used because the reviewed study inventory was attributed to 1 kg of fabric [13].

LCA from cradle to gate was applied and covers the following processes: fibre extraction, yarn production, weaving preparation (sizing), weaving, pre-treatment, continuous dyeing, and fabric finishing. A more detailed description of the processes is given in the study by V. Wagner *et al.* [13]. The LCA was performed according to ISO 14040/14044 standards. The *SimaPro* 9.5 software was used for the analysis. Input datasets were taken from the *Ecoinvent* 3.8 database. The *ReCiPe* Midpoint (H) V1.08 life cycle impact assessment method was chosen [13].

3. RESULTS

3.1. Literature Analysis on Blended Textile Environmental Impact Assessment

3.1.1. Bibliometric Analysis

As a result, 31 keywords were identified that occurred 12 or more times. The keywords were linked by 278 links and formed four clusters. The keywords and their links are shown in Fig. 2. The most popular keyword was waste (36 occurrences), followed by textile (35 occurrences), and next came life cycle assessment and wastewater (34 occurrences). Looking at the total link strength, the order was similar, except for the second strongest connection, shown by sustainability, indicating a high correlation with other words, although occurring less than other words.

The largest cluster was around the keyword wastewater and degradation, indicating that much of the research in this area deals with textile wastewater and textile end-of-life. The next cluster in size was around the keywords waste and textiles, linking words such as mechanical performance, showing that research is also being done on the technical side of blended textiles. The last cluster, which was of considerable size, was around the keyword life cycle assessment, meaning that studies are carried out on the environmental impact of blended textiles over their whole life cycle, taking into account sustainability and circular economy aspects.

An important finding was that life cycle assessment is not closely linked to wastewater, as it is not linked to terms such as wastewater, toxicity, and heavy metals. This suggests that existing LCA studies on blended textiles are likely to pay little attention to the wastewater and its toxic effects. Also, keywords related to greenhouse gas emissions do not appear, which means that this aspect has not been sufficiently researched or may not be relevant when considering the environmental impact of a blended textile.
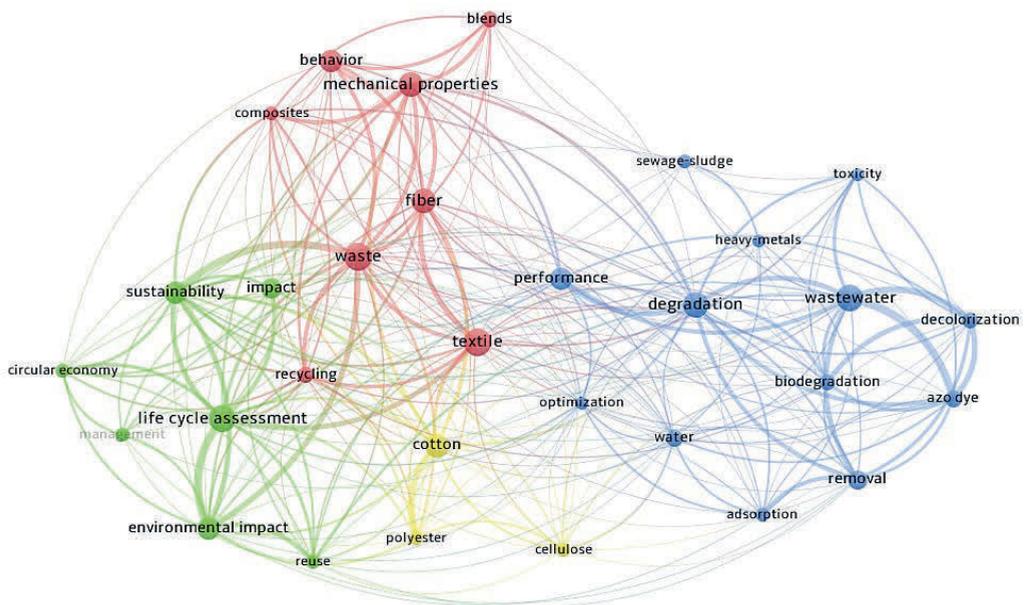
Fig. 2. Keyword co-occurrence with a threshold of at least 12 occurrences.

3.1.2. Environmental Assessment of the Production of Cotton and Polyester Blends

Many review and research studies were reviewed before it was possible to compile studies on the environmental impacts of CO/PES production relevant to this study. Most of the reviewed research does not directly address the CO/PES blend production [15], [36], use generic data [23], use pre-built processes from databases such as *Ecoinvent* [37], or do not give detailed input data [22]. It was confirmed that no complete LCI on CO/PES production is available in the literature. However, several studies and reports were found with data partially covering production, see Table 1.

TABLE 1. STUDIES AND REPORTS THAT PARTIALLY COVER DATA ON THE ENVIRONMENTAL IMPACT OF CO/PES PRODUCTION

Product	Material	Functional unit	Processes covered	Data covered	General assumption	Publication year	Source
Medical workwear	CO/PES	woven doctor's trousers in white with cotton-polyester yarn (35/65), 470 dtex	yarn spinning, sizing, weaving, pre-treatment, dyeing and finishing	Input: Energy, water, chemicals. Output: water emissions, waste	All data taken from cotton production except for yarn spinning	2023	[13]
Fabric	CO/PES	2 tons of polyester-cotton product	pre-treatment, dyeing and finishing	Input: Energy, water, chemicals. Output: water emissions, air emissions	Data were obtained from commercial companies, but it is not specified what, if any, assumptions were made	2018	[38]
Hospital uniform	CO/PES	hospital uniform, cotton-polyester weave	yarn spinning, weaving, dyeing and finishing	Input: Energy, water, chemicals Output: water emissions, air emissions, waste	Excluding sizing and de-sizing, and only dyeing is specifically for CO/PES	2019	[21]
Fabric	CO/PES	100 kg of cotton-polyester fabric	pre-treatment, dyeing	Input: Energy, water, chemicals Output: water emissions	The data is from a company report, but potentially outdated	2003	[39]
Fabric (BAT)	CO and CO blends	n/a	pre-treatment, dyeing and finishing	Input: Energy, water, chemicals	Cotton and cotton blends are assumed to have the same input parameters, except at the finishing stage	2023	[40]

The most complete LCI on CO/PES production was included in the Wagner *et al*. LCA study [13]. It includes data on primary inputs such as energy and water, which are included in several studies reviewed. Still, it also provides a detailed list of chemicals used and the wastewater characteristics for each process. For complete data, there is a lack of data on air emissions. However, the main problem is that all data are taken for cotton production [35], as the authors found that no data on CO/PES production were available in the literature.

A literature review led to a study on CO/PES fabrics, which included LCI [38]. The data for the study are collected from companies and include data on pre-treatment, dyeing, and finishing. The LCI provides air emissions that were not covered by the previously discussed research, but input parameters and water emissions are limited. Only lye (NaOH) and dyes are listed as input chemicals as they are one of the most important inputs in the production process. The data acquisition and assumptions are also not described, only the fact that the data were obtained from commercial businesses.

The lack of data in the literature on textile input chemicals was also recognized by Roos *et al*. who carried out a study to develop a nomenclature system for textile-related chemicals, that was used to create a generic chemical inventory for use in LCA of textiles [21]. LCI data for several key textile manufacturing processes were collected and compiled into LCI datasets. In addition, LCA was also carried out for some textile products using the established LCI. One was a hospital uniform made of a CO/PES blend. However, the study only looked at one process specifically for the CO/PES mixture – dyeing. Also, the sizing and de-sizing, which uses many chemicals in the pre-weaving and pre-treatment process [13], was not included.

As no other studies were available in the scientific literature that included the required data, various reports were reviewed. For further analysis, the B05 company report and the Best Available Techniques (BAT) for the textile industry report were selected [39], [40]. For company B05, the environmental impact of CO/PES fabric production was reported [39]. Only two processes were reported, and no detailed emission data are available. Furthermore, the report was prepared in 2003, and production technologies have evolved since then, so the data may be outdated.

Unlike the previous case, the BAT report summarizes all current developments in the textile industry [40]. However, this was not an exception, as relatively little attention was paid to textile blends, and in several cases, cotton and cotton blends were assumed to have the same processing and production processes. This may be correct in some cases, but incorrect in others, for instance the dyeing process requires an additional dyeing stage to colour the PES part of the blend in order to obtain a dark colour [41]. This needs to be clarified in order to avoid the assumption that in all cases the same raw materials and processes can be adopted for the production of CO blends as for the production of CO. Emissions from textile production were also considered more qualitatively, and no specific data was compiled to provide insight into the reference values for water and air emissions in the textile industry.

To better understand the differences between the studies, the process-specific data from each study were analysed, and then the values of the shared parameters were summarized in Table 2 and Table 3. It should be noted that these are only the shared parameters, and the tables do not show the other input parameters for each case.

Table 2 summarizes the overlapping input chemicals for three processes – pre-treatment, dyeing, and finishing. Data for the other processes are not included as they were only listed in one study [13]. A switch to the same units of measurement was made to allow the values to be compared with each other. Comparing the input values, it can be observed that inputs like enzymes have quite small variations, on the other hand, some inputs such as sodium dithionite and sodium hydroxide vary considerably. This variation might be driven by the

desired properties of the final product – its colour, fastness, etc. [42]. Also are likely due to the different treatment steps and technologies involved in the main processes in each situation, as well as the exclusion of other input chemicals that could smooth out the overall difference. It should also be noted that there are no completely overlapping parameters, indicating that there are no essential chemicals used in all variations of the process and included in the LCI.

TABLE 2. COMPILATION OF OVERLAPPING DATA FROM SELECTED STUDIES AND REPORTS (CHEMICALS)

	CO (Medical workwear) [13], [35]	CO and CO/PES (BAT)* [40]	CO/PES (Hospital uniform) [21]	CO/PES (Fabric, B05 company)** [39]	CO/PES (Fabric) [38]
Pre-treatment					
Enzymes, g kg^{-1}	4.8	5	–	–	–
Hydrogen peroxide (H$_2$O$_2$), g kg^{-1}	35.4	10	–	65	–
Non-ionic and ionic surfactant/ Wetting agents, g kg^{-1}	0.05	23.5	–	–	–
Sodium hydroxide (NaOH), g kg^{-1}	472.5	452	–	20	7000
Stabilizing agent, g kg^{-1}	–	5	–	25.3	–
Sodium silicate/Detergent, g kg^{-1}	–	14	–	48	–
Dyeing					
Sodium dithionite/Sodium hydrosulphite, g kg^{-1}	2.4	–	–	3472	–
Hydrogen peroxide (H$_2$O$_2$), g kg^{-1}	–	–	10	19.5	–
Non–ionic and ionic surfactant/ Wetting agents, g kg^{-1}	0.02	108	4	–	–
Sodium hydroxide (NaOH), g kg^{-1}	65.3	–	12	42.5	–
Sequestering agents, g kg^{-1}	–	144	6	–	–
Anti-migration agent, g kg^{-1}	–	900	–	198.4	–
Acetic acid/Vinegar, g kg^{-1}	5	57.6	52	–	–
Vat dye, g kg^{-1}	–	–	20	520.8	33
Reactive dye, g kg^{-1}	–	–	20	–	–
Disperse dye, g kg^{-1}	–	–	–	54.6	–
Finishing					
Softener, g kg^{-1}	16.2	920	–	–	–
Acid/Acetic acid, g kg^{-1}	5.1	11.5	–	–	–

* In some cases, the chemicals were given as g L^{-1} water but no water consumption was provided, so to get g kg^{-1} water consumption was taken from V. Wagner *et al*. study [13].
** In the study, several input chemicals were given as mL kg^{-1}, which were converted to g kg^{-1} using density.

Energy and water data were compiled the same way as for chemicals (see Table 3). It can again be observed that there are cases where the differences are minimal, such as water consumption in finishing, and there are also very significant variations, such as water and wastewater in pre-treatment. The least data are available for thermal energy. Zhang *et al.* included in their inventory the amount of coal used, which was most likely used for heating but due to insufficient information, this was not included [38]. The BAT report provides only

general data on energy and water consumption in the textile industry but no data on specific materials and processes, except for water consumption in pre-treatment [40].

TABLE 3. COMPILATION OF OVERLAPPING DATA FROM SELECTED STUDIES AND REPORTS (ENERGY AND WATER)

	CO (Medical workwear) [13], [35]	CO and CO/PES (BAT) [40]	CO/PES (Hospital uniform) [21]	CO/PES (Fabric, B05 company) [39]	CO/PES (Fabric) [38]
Pretreatment					
Electricity, kWh kg⁻¹	0.036	–	–	0.049	3.55
Water, L kg⁻¹	–	23	–	23.24	615.50
Wastewater, L kg⁻¹	15.10	–	–	20.40	350
Heat, kWh kg⁻¹	0.16	–	–	–	–
Dyeing					
Electricity, kWh kg⁻¹	0.19	–	0.70	0.014	0.45
Water, L kg⁻¹	72.72	–	75	24.80	12
Wastewater, L kg⁻¹	33.35	–	–	19.50	–
Heat, kWh kg⁻¹	1.84	–	8.33	–	–
Finishing					
Electricity, kWh kg⁻¹	0.16	–	–	–	0.31
Water, L kg⁻¹	23.30	–	–	–	22.90
Wastewater, L kg⁻¹	8.35	–	–	–	19.75
Heat, kWh kg⁻¹	0.56	–	–	–	–

The least included data in the reviewed environmental assessments are water and air emissions. This is consistent with the conclusion of the bibliometric analysis that LCAs and wastewater show no connection. This should not be the case because when it comes to the environmental impact of textile production, much focus is on the toxicity of wastewater [43]. Therefore, LCA studies should also include this aspect to assess blended textiles' environmental impact fully. Only the study about medical workwear includes a detailed composition of the textile wastewater but it is taken from the cotton production [13]. Other studies only include the Chemical Oxygen Demand (COD) [21], [38], [39], which is the most significant component by weight [43]. Therefore, one of the objectives of the following analysis is to find out whether the exclusion of wastewater significantly impacts the results.

It is not possible to develop a comprehensive LCI for CO/PES blended textiles using the data from the literature analysis because some data are unavailable, the differences in the available data are too large, and the assumptions on processes and technologies are not fully clear. Therefore, scenario-based LCA was carried out to see how the differences in available data affect the environmental impact results for CO/PES blends.

3.1.3. Ecoinvent Processes

Following the literature review, the *Ecoinvent* database was checked to assess whether built-in CO/PES production datasets are available. The database includes a textile category in materials and process sections, which contains datasets on textiles and the processes used in their production and use. The materials did not include CO/PES textile material, from which it would have been possible to see input data for its production. Cotton and polyester fibres were available and were used further in the LCA modelling.

Also, in terms of processes, there were no built-in processes specifically for the CO/PES blend. Still, there were various processes for cotton and polyester separately, although not all of them. For example, data on the sizing process was again missing. Processes that could be used for CO/PES modelling with assumptions are synthetic fibre weaving, cotton fibre continuous dyeing, and finishing cotton woven textiles.

3.1.4. Product Category Rules and Uncertainty Threshold

Several textile related PCRs were considered. According to the United Nations Central Product Classification, the most appropriate PCR was selected, being PCR 2022:04 Fabrics [44]. The guidelines cover system boundaries, data quality requirements, allocation and other key aspects of LCA. However, there is no mention of waste water and its composition or direct emissions to the air. For input parameters, a 1 % cut-off rule is included, which means that 99 % of input variables should be included in the inventory according to their influence on impact categories, mass and energy. These guidelines are mandatory for the development of EPDs, not for research, but they provide an overview of what a complete LCI should look like.

The review of the standards and the study revealed that there is no strict and universal threshold that can be used to assess the uncertainty of results in impact categories [20], [32]–[34]. It was therefore decided to assess the uncertainties qualitatively, based on their potential impact on the ability to establish the LCI and perform the LCA for the CO/PES blended textile.

3.2. Uncertainty Identification through Scenario-Based Life Cycle Assessment

The LCA study on the medical workwear [13], having the most detailed LCI, was used as the baseline model. It is also the only study to include all manufacturing processes. See Tables 2 and 3 for all input parameter values. Scenarios were created for all studies and reports, summarized in Table 1. The scenarios were built by changing the parameters outlined in Table 2 and Table 3 that were shared with the baseline scenario study. In addition, it was decided to make an exception and add water consumption in the pre-treatment process to the scenarios, although it is not included in the baseline scenario. This was done because it was found in all studies that looked at this process except the baseline case. The changed parameters are shown in Table 4.

TABLE 4. SCENARIOS CREATED AND PARAMETERS CHANGED IN THE PROCESSES

Processes	Scenario 2 (BAT) [40]	Scenario 3 (hospital uniform) [21]	Scenario 4 (B05 company) [39]	Scenario 5 (fabric) [38]
Pretreatment	Enzymes; Hydrogen peroxide; Non-ionic and ionic surfactant/Wetting agents; Sodium Hydroxide; Water	–	Hydrogen peroxide; Sodium Hydroxide; Electricity; Water; Wastewater	Sodium Hydroxide; Electricity; Water; Wastewater
Dyeing	Non-ionic and ionic surfactant/Wetting agents	Non-ionic and ionic surfactant/Wetting agents; Sodium Hydroxide; Acetic acid/Vinegar; Electricity; Water; Heat	Sodium dithionite/Sodium hydrosulphite; Sodium Hydroxide; Electricity; Water; Wastewater	Electricity; Water
Finishing	Softener; Acid/Acetic acid	–	–	Electricity; Water; Wastewater

The scenarios were built without water emissions, as water emissions were only included in the baseline scenario study, so there are no shared parameters to change. However, when carrying out an LCA for textiles, water emissions should be included. In this case, they can be excluded as uncertainty will be assessed rather than specific environmental impacts.

In addition, a scenario was created using built-in *Ecoinvent* processes – the weaving of synthetic fibres, continuous dyeing of cotton fibres, and finishing of cotton woven textiles. For built-in processes, emissions are kept in as the *Ecoinvent* processes include not only direct emissions but also indirect emissions. The reason for this is that it is modelled using inputs from nature rather than from the techno sphere, as the authors of the process have to manually align the emissions. Therefore, it is not possible without in-depth research to distinguish which emissions are direct in order to remove them.

3.2.1. *Impact Categories and Production Processes*

First, the baseline scenario was analysed, looking specifically at the distribution of the impact of production processes. Life cycle impact assessment provides results for several impact categories. The chosen method has 18 impact categories, each with a corresponding unit of measurement. However, to compare the categories, switching to a common unit of measurement is necessary. This is achieved through normalization. It is the process of normalizing the impact categories to a single dimension and presenting the results in a broader context that indicates the impact of each category in relation to the overall environmental impact [45]. The normalized values for the baseline scenario are shown in Fig. 3. All categories with normalized values greater than 0.0020 are included in the graph, except for global warming (0.0016), which was also included as a widely used category in environmental impact assessments. It should be noted that the results are not original, as the model is based on an existing study [13]. However, the results are not presented and analysed this way, so the following observations are original.
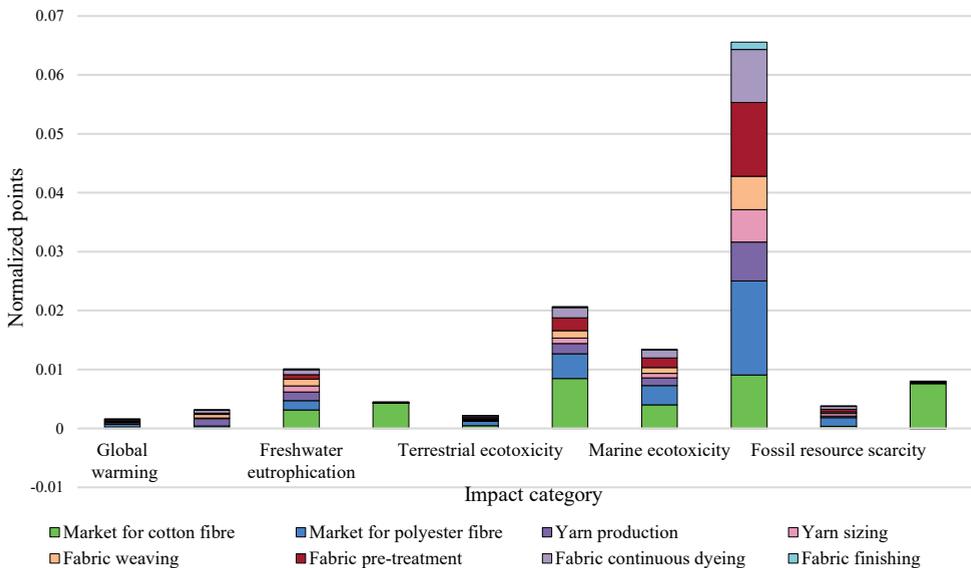
Fig. 3. Normalised results by impact categories for the baseline scenario of cotton and polyester blend production.

It can be observed that the main impact categories are related to toxicity – human carcinogenic toxicity, marine ecotoxicity, and freshwater ecotoxicity. This underlines the importance of having a complete LCI with chemicals, as they are a major source of toxicity. Of the input chemicals, sodium hydroxide had the highest impact, which is explained by the quantity used, as sodium dithionite has the highest impact in Scenario 4, which is based on data from company B05. It is also important to note that the global warming category has a relatively small impact on overall environmental impact. This should be taken into account when analysing the environmental performance of textiles.

Looking at the breakdown of the processes involved, the extraction of raw materials - cotton and polyester fibres - has the highest environmental impact, followed by pre-treatment. Note that this is for the baseline scenario, as the distribution of impact changes when looking at other scenarios. The reference study shows similar results [13], as the second largest impact was related to the extraction of raw materials, while the first was related to the use phase, which is outside this study's scope.

3.2.2. Wastewater Importance

One of the objectives of the analysis was to find out whether the exclusion of water emissions from the LCI significantly changes the results. Therefore, two baseline scenarios were developed – with and without water emissions. The results were then compared with each other, and it was found that 12 of the 18 impact categories had the same results. The results differed significantly in the six categories shown in Fig. 4. These categories have the highest environmental impact compared to the rest, as depicted in Fig. 2, except the human non-carcinogenic toxicity, which shows the highest variation but is not as influential as the others. In contrast, the 10 % difference is shown by human carcinogenic toxicity, which has the highest environmental impact of all categories. Overall, these results show that detailed water emissions are justified to be included in the LCI as they affect the main environmental impact categories in the context of blended textile production.
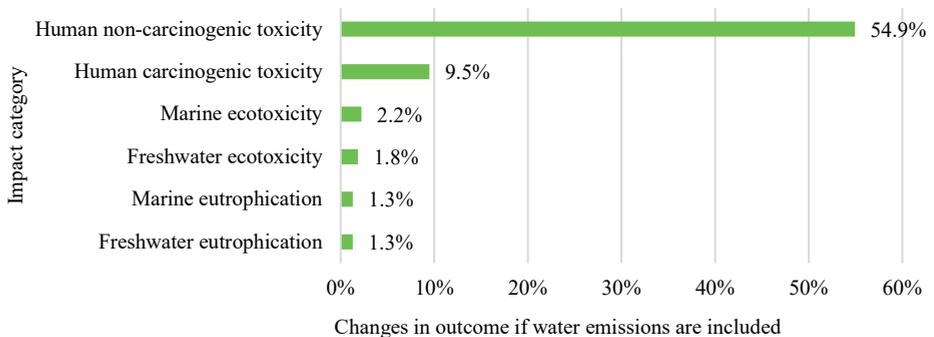
Fig. 4. Variation of results by including detailed water emissions in the production of cotton and polyester blends.

3.2.3. Comparison of Scenarios

As mentioned previously, the aim of this study is not to obtain specific quantitative results but to look at the differences in results. Therefore, the results obtained for each scenario were compared with the baseline scenarios without water emissions and expressed as percentage differences. Fig. 5 summarizes the results obtained in the scenarios for all impact categories.
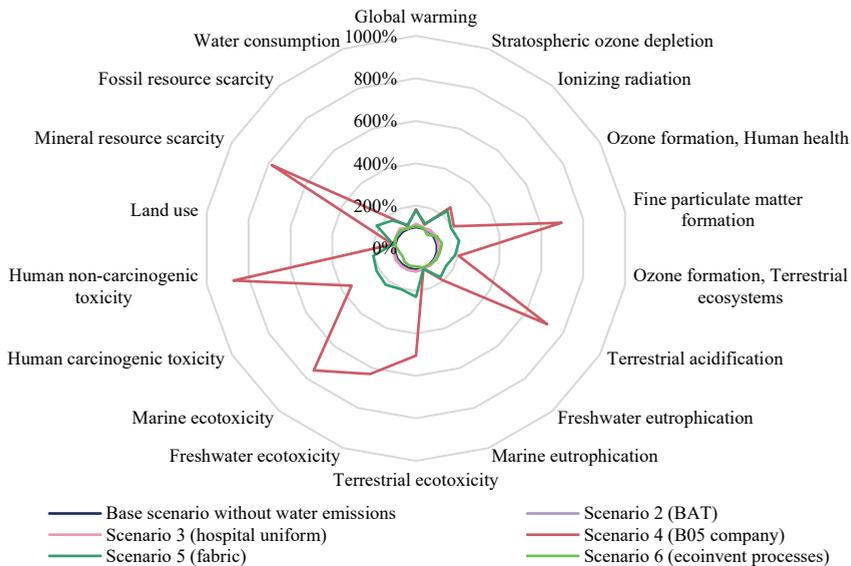
Fig. 5. Comparison of the results by impact categories, using the baseline scenario without water emissions as reference.

Scenarios 2 and 3 show the lowest differences from literature-based scenarios compared to the baseline scenario without water emissions, with average differences of 6 % and 8 %, respectively. These scenarios are based on a BAT and hospital uniform study [21], [40]. The slight difference could be explained by the fact that the sources provide the least data on energy and water, which underlines the importance of these data, and the Scenario 3 study only had data on one of the three processes. The graph also shows that none of the literature-based scenarios have lower environmental impacts than the baseline scenario. This means that the baseline scenario is the best-case scenario regarding environmental impact, at least according to the data available in the literature. However, it is mainly based on cotton production, so it cannot be considered the best option in all cases for the assessment of blended textiles. Although in this specific case it might be that only cotton is treated with dye, yielding a light colour for the final textile, this outcome would not be desirable for all use cases, therefor the same LCI would not be applicable.

Scenario 6 with *Ecoinvent* processes showed, on average, only a 1 % difference from the baseline, but the environmental impacts were lower in some categories. Yet the outcome shows that there is no need to make bigger assumptions and make the model more general by using the built-in processes of *Ecoinvent*.

The most significant changes are found in scenarios 4 and 5, with an average of 288 % and 81 %, respectively. Scenario 5 is based on the Zhang *et al.* study [38], which specifically looked at a blend of CO/PES but used limited input data. In this scenario, only two chemicals were altered, but almost all water and energy inputs were changed, indicating that the water and energy data were most likely responsible for the large changes. Not all processes for producing CO/PES materials are the same, and the choice of process depends largely on the type of finished material and its end use. Consequently, water and energy consumption will vary depending on applied processes and used technologies. On the other hand, it is better to compare parameters for similar end products, such as hospital uniforms in Scenario 3 and in the baseline scenario, as the production processes are more likely to match. In Scenario 5, as

in Scenario 4, only four categories are relatively consistent with the baseline scenario – stratospheric ozone depletion, marine eutrophication, land use, and water consumption. The water consumption category does not change significantly, although water consumption increases in Scenario 5, as the impact of this category is mainly driven by cotton extraction.

In the scenario 4, the variation ranges from 3 % to 772 %. This scenario has the most changes in input parameters. Sodium dithionite has the greatest impact as it is used in very high quantities compared to the baseline scenario. Considering that the data for this scenario is from 2003 [39], it is also possible that outdated technologies are causing major changes in results. The graph shows strong peaks for eight categories, exceeding a difference of 350 %. Five of these categories have relatively significant environmental impacts, as shown in Fig. 3. Scenarios 4 and 5 show that results can vary significantly based on the data available in the literature and underline the need for a specific LCI for CO/PES blends.

4. CONCLUSION

A review of the environmental impact assessment studies on CO/PES blends revealed a knowledge gap: several studies have been carried out on the environmental impact of this material, but they do not include a comprehensive LCI. Therefore, the aim of the study was to conduct a literature review on the environmental assessment of the production of CO/PES blends and to identify what assumptions have been made so far and how these assumptions might affect the environmental assessment. A literature analysis was carried out to achieve the objective, including a bibliometric analysis and a review of the scientific literature and the *Ecoinvent* database. The results were used for scenario-based LCA to determine the possible effects of assumptions and data variations on environmental impacts.

A bibliometric analysis of the environmental impact of blended textiles revealed that studies fall into three main groups, covering textile wastewater and end-of-life, the technical side and life cycle assessments. A key finding was that existing LCA studies on blended textiles are unlikely to cover the effects and toxicity of wastewater. Greenhouse gases also appear to be understudied or possibly irrelevant in assessing blended textiles' environmental impacts. This was confirmed by further literature review.

Most of the environmental impact studies on blended textiles do not directly address the production of CO/PES blends, use generic data, or do not provide detailed input data. However, it was possible to summarize five studies and reports that provide some relevant data to move toward a complete LCI. They revealed that the environmental impacts of the sizing process, as well as water and air emissions, are mostly overlooked. Overall, it can be concluded that it is not possible to develop a comprehensive LCI for the CO/PES blend using the data available in the literature. Nevertheless, scenario-based LCA was performed to see what would happen if one tried to establish a complete LCI using the available data.

The scenario-based LCA highlighted the importance of considering input chemicals when addressing blended textiles, something that is often overlooked in practice. These chemicals lead to toxic environmental impacts. Furthermore, while comparing and evaluating blended textiles, it is crucial to concentrate on toxicity categories, such as human carcinogenic toxicity, rather than global warming indicators, as they are more influential for the environmental impact. It is also essential to include a detailed composition of the wastewater as it affects the main environmental impact categories. Finally, the LCA showed that differences in the data available in the literature can lead to considerable uncertainties in results, sometimes as much as eight times more different results. The resulting uncertainties suggests that assumptions and data sources need to be carefully evaluated before use and should be standardized to produce reliable results. Thus, a more detailed database is needed

to develop product-specific LCIs for blended textiles in order to avoid such significant uncertainties in future environmental assessments.

The final product and its required properties influence the production processes and technologies chosen, which in turn have an impact on the consumption of chemicals, water and electricity. The main process that determines the chemicals used in textile production is dying. When dyeing blended textiles, there are cases where only CO can be dyed if a light colour is desired. On the other hand, if a darker and brighter colour is desired, both components of the mixture must be dyed; either in one bath or two bath processes. This indicates that there are times when the processes for producing cotton and CO/PES blends may overlap. However, there are cases where the input parameters for a CO/PES blend cannot be considered to be the same as for CO. This largely depends on the colour fastness to washing and/or rubbing as well the other required end characteristics. Thus, when performing an LCA on a blended textile, it is necessary to assess these factors to know which input data to choose. This leads back to the functional unit that describes the amount with defined functions and properties, allowing later comparison of the impact of products providing the same functionality.

The results of this study can be used to understand better what has been done so far and what is missing in the literature. Identified knowledge gaps can be further explored and improved. The main objective was to highlight the impact of knowledge gaps on future research in this area. Further, a primary data collection study is needed to achieve the final goal, which is a life cycle assessment for a blended CO/PES textile. It should be noted that the scenario-based LCA made many assumptions, so the results cannot be used quantitatively and separately and can only be used in the context intended by this study.

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REFERENCES

[1] Horn S., Mölsä K. M., Sorvari J., Tuovila H., Heikkilä P. Environmental sustainability assessment of a polyester T-shirt – Comparison of circularity strategies. *Science of The Total Environment* 2023:884:163821. https://doi.org/10.1016/j.scitotenv.2023.163821

[2] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions EU. Strategy for Sustainable and Circular Textiles. Brussels, 30.3.2022.

[3] Stone C., Windsor F. M., Munday M., Durance I. Natural or synthetic – how global trends in textile usage threaten freshwater environments. *Science of The Total Environment* 2020:718:134689. https://doi.org/10.1016/j.scitotenv.2019.134689

[4] Sohn J., Nielsen K. S., Birkved M., Joanes T., Gwozdz W. The environmental impacts of clothing: Evidence from United States and three European countries. *Sustainable Production and Consumption* 2021:27:2153–2164. https://doi.org/10.1016/j.spc.2021.05.013

[5] Jana P. Challenges in the Traditional Fashion and Textile Supply Chain. In *Lean Supply Chain Management in Fashion and Textile Industry*, in *Textile Science and Clothing Technology*. Springer, Singapore, 2022. https://doi.org/10.1007/978-981-19-2108-7_2

[6] Kahoush M., Kadi N. Towards sustainable textile sector: Fractionation and separation of cotton/ polyester fibers from blended textile waste. *Sustainable Materials and Technologies* 2022:34:e00513. https://doi.org/10.1016/j.susmat.2022.e00513

[7] Juanga-Labayen J. P., Labayen I. V., Yuan Q. A Review on Textile Recycling Practices and Challenges. *Textiles* 2022:2(1):174–188. https://doi.org/10.3390/textiles2010010

[8] Karthik T., Gopalakrishnan D. Environmental Analysis of Textile Value Chain: An Overview. In *Roadmap to Sustainable Textiles and Clothing*, in *Textile Science and Clothing Technology*. Springer, Singapore, 2014. https://doi.org/10.1007/978-981-287-110-7_6

[9] Palacios-Mateo C., Van Der Meer Y., Seide G. Analysis of the polyester clothing value chain to identify key intervention points for sustainability. *Environmental Sciences Europe* 2021:33(1):2. https://doi.org/10.1186/s12302-020-00447-x

[10] Ellen MacArthur Foundation. A new textiles economy: Redesigning fashion's future. 2017.

[11] Wang S., Salmon S. Progress toward Circularity of Polyester and Cotton Textiles. *Sustainable Chemistry* 2022:3(3):376–403. https://doi.org/10.3390/suschem3030024

[12] Zandberga A., Kalnins S. N., Gusca J. Decision-making Algorithm for Waste Recovery Options. Review on Textile Waste Derived Products. *Environmental and Climate Technologies* 2023:27(1):137–149. https://doi.org/10.2478/rtuect-2023-0011

[13] Wagner V., Keil M., Lang-Koetz C., Viere T. Screening life cycle assessment of medical workwear and potential mitigation scenarios. *Sustainable Production and Consumption* 2023:40:602–612. https://doi.org/10.1016/j.spc.2023.07.026

[14] Gonçalves A., Silva C. Looking for sustainability scoring in apparel: A review on environmental footprint, social impacts and transparency. *Energies* 2021:14(11):3032. https://doi.org/10.3390/en14113032

[15] Munasinghe P., Druckman A., Dissanayake D. G. K. A systematic review of the life cycle inventory of clothing. *Journal of Cleaner Production* 2021:320:128852. https://doi.org/10.1016/j.jclepro.2021.128852

[16] Van Der Velden N. M., Patel M. K., Vogtländer J. G. LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *Int J Life Cycle Assess* 2014:19(2):331–356. https://doi.org/10.1007/s11367-013-0626-9

[17] Zhang S., Xu C., Xie R., Yu H., Sun M., Li F. Environmental assessment of fabric wet processing from gate-to-gate perspective: Comparative study of weaving and materials. *Science of The Total Environment* 2023:857:159495. https://doi.org/10.1016/j.scitotenv.2022.159495

[18] Sandin G., Peters G. M. Environmental impact of textile reuse and recycling – A review. *Journal of Cleaner Production* 2018:184:353–365. https://doi.org/10.1016/j.jclepro.2018.02.266

[19] Barahmand Z., Eikeland M. S. Life Cycle Assessment under Uncertainty: A Scoping Review. *World* 2022:3(3):692–717. https://doi.org/10.3390/world3030039

[20] Hauschild M. Z., Rosenbaum R. K., Olsen S. I. Eds. *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing, 2018. https://doi.org/10.1007/978-3-319-56475-3

[21] Roos S., Jönsson C., Posner S., Arvidsson R., Svanström M. An inventory framework for inclusion of textile chemicals in life cycle assessment. *Int J Life Cycle Assess* 2019:24(5):838–847. https://doi.org/10.1007/s11367-018-1537-6

[22] Anh Dao Tran T., Thauvin E., Ferraz F., Drean E., Schacher L., Dominique A. Comparative Life Cycle Assessment of Dental Scrubs Made of Polyester/Cotton and 100% Cotton. In *Advances in Applied Research on Textile and Materials – IX*, vol. 17, Msahli S., Debbabi F., (Eds.), in *Springer Proceedings in Materials*. Cham: Springer International Publishing 2022:320–327. https://doi.org/10.1007/978-3-031-08842-1_51

[23] Snigdha M. Hiloidhari, Bandyopadhyay S. Environmental footprints of disposable and reusable personal protective equipment – a product life cycle approach for body coveralls. *Journal of Cleaner Production* 2023:394:136166. https://doi.org/10.1016/j.jclepro.2023.136166

[24] Narendra A. S. G. Accelerated Bleaching of Cotton Material with Hydrogen Peroxide. *J Textile Sci Eng* 2013:03:04. https://doi.org/10.4172/2165-8064.1000140

[25] Voglhuber-Slavinsky A. *et al.* Setting life cycle assessment (LCA) in a future-oriented context: the combination of qualitative scenarios and LCA in the agri-food sector. *European Journal of Futures Research* 2022:10(1):15. https://doi.org/10.1186/s40309-022-00203-9

[26] Benitez A., Wulf C., Steubing B., Geldermann J. Scenario-based LCA for assessing the future environmental impacts of wind offshore energy: An exemplary analysis for a 9.5-MW wind turbine in Germany. *Energy, Sustainability and Society* 2024:14(1):49. https://doi.org/10.1186/s13705-024-00474-z

[27] Rossi F., Zuffi C., Parisi M. L., Fiaschi D., Manfrida G. Comparative scenario-based LCA of renewable energy technologies focused on the end-of-life evaluation. *Journal of Cleaner Production* 2023:405:136931. https://doi.org/10.1016/j.jclepro.2023.136931

[28] Dolge K., Blumberga D. What are the Linkages between Climate and Economy? Bibliometric Analysis. *Environmental and Climate Technologies* 2022:26(1):616–629. https://doi.org/10.2478/rtuect-2022-0047

[29] Mohadab M. E., Bouikhalene B., Safi S. Bibliometric method for mapping the state of the art of scientific production in Covid-19. *Chaos, Solitons & Fractals* 2020:139:110052. https://doi.org/10.1016/j.chaos.2020.110052

[30] Introduction to the Database. Ecoinvent. [Online]. [Accessed: 15.04.2024]. Available: https://support.ecoinvent.org/introduction-to-the-database

[31] Product Category Rules. The International EPD® System. [Online]. [Accessed: 22.10.2024]. Available: https://www.environdec.com/product-category-rules-pcr/the-pcr

[32] International Organization for Standardization. Environmental Management – Life Cycle Assessment – Principles and Framework (ISO Standard No. 14040:2006). ISO 14040:2006, 2006. [Online]. [Accessed: 22.10.2024]. Available: https://www.iso.org/standard/37456.html

[33] International Organization for Standardization. Environmental Management — Life Cycle Assessment — Requirements and Guidelines (ISO Standard No. 14044:2006), 14044:2006, 2006. [Online]. [Accessed: 22.10.2024]. Available: https://www.iso.org/standard/38498.html

[34] European Commission. Joint Research Centre, and Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook -General guide for Life Cycle Assessment, Detailed guidance. Publications Office of the European Union, 2010.

[35] Jewell J., Koffler C., Murphy S. LCA Update of Cotton Fiber and Fabric Life Cycle Inventory. Cotton Incorporated. 2017. [Online]. [Accessed: 25.01.2024]. Available: http://resource.cottoninc.com/LCA/2016-LCA-Full-Report-Update.pdf

[36] Subramanian K., Chopra S. S., Cakin E., Li X., Lin C. S. K. Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup. *Resources, Conservation and Recycling* 2020:161:104989. https://doi.org/10.1016/j.resconrec.2020.104989

[37] Zhao M. *et al.* Virtual carbon and water flows embodied in global fashion trade – a case study of denim products. *Journal of Cleaner Production* 2021:303:127080. https://doi.org/10.1016/j.jclepro.2021.127080

[38] Zhang Y. *et al.* Improved design for textile production process based on life cycle assessment. *Clean Techn Environ Policy* 2018:20(6):1355–1365. https://doi.org/10.1007/s10098-018-1572-9

[39] Sara B., Tarantini M. Life Cycle Assessment of cotton/polyester fabric in B05 company. Nov. 2003. Accessed: Feb. 15, 2024. [Online]. [Accessed 22.10.2024]. Available: http://spring.bologna.enea.it/towefo/results_public_area/D20%20LCA/D20%20LCA_B05.pdf

[40] European Commission. Joint Research Centre. Best available techniques (BAT) reference document for the textiles industry: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). LU: Publications Office, 2023.

[41] Foisal A. B. M., Ahmed M. T. Dyeing of Polyester/Cotton Blended Woven Fabric in One Bath. *SEU Journal of Science and Engineering* 2017:11(2). [Online]. Available: https://seu.edu.bd/seujse/downloads/vol_11_no_2_dec_2017/01_Vol11No2Dec2017.pdf

[42] Hossain I., Moniruzzaman Md., Maniruzzaman Md., Jalil M. A. Investigation of the effect of different process variables on color and physical properties of viscose and cotton knitted fabrics. *Heliyon* 2021:7(8):e07735. https://doi.org/10.1016/j.heliyon.2021.e07735

[43] Wang X., Jiang J., Gao W. Reviewing textile wastewater produced by industries: characteristics, environmental impacts, and treatment strategies. *Water Science and Technology* 2022:85(7):2076–2096. https://doi.org/10.2166/wst.2022.088

[44] PCR 2022:04 Fabrics (1.0.1). The International EPD® System, Aug. 2022. Accessed: Oct. 23, 2024. [Online]. Available: https://api.environdec.com/api/v1/EPDLibrary/Files/b5abeb35-253e-49df-14ac-08da85915ae2/Data

[45] Ige O. E., Olanrewaju O. A., Duffy K. J., Collins O. C. Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method. *Energies* 2022:15(7):2708. https://doi.org/10.3390/en15072708

Review

Unleashing Energy Potential: Insights of Energy Audit Practices

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Abstract: This article examines energy audit procedures as a crucial instrument for raising building and business energy efficiency in European Union (EU) Member States. Energy audits, which include technical, economic, and environmental aspects, are essential to reaching the EU's climate targets, which include increasing energy independence and cutting emissions by 55% by 2030. The study highlights how crucial energy efficiency initiatives are to combating climate change, cutting energy use, and advancing sustainable development. A thorough examination of methods, financing sources, and legislative frameworks reveals differences in how Member States carry out directives such as the Energy Performance of Buildings Directive and the Energy Efficiency Directive. A case study on Latvia is included in the article, highlighting the country's energy audit regulations, implementation difficulties, and successes. This study applied a bibliographic methodology or review of the scientific and other relevant literature, analyzing sources identified through targeted keyword searches in academic databases and a variety of online sources, including official legal websites, handbooks, reports, plans, and other publicly available digital resources. The integration of energy efficiency principles and country performances are compared using data from the Odyssee and Mure databases. The results highlight how important it is to standardize energy auditing practices, promote information sharing across national borders, and move past obstacles like public resistance and budgetary limitations. Policy recommendations to improve energy efficiency and aid the EU's transition to climate neutrality by 2050 are included in the research's conclusion.

Keywords: energy audit; energy efficiency; reduction in greenhouse gas emissions; electricity consumption; energy efficiency management

1. Introduction

It is clear that the climate crisis is a global problem and requires coordinated actions on different levels, from household to enterprise, until country leaders tackle it [1]. Combined policy strategies can help overcome complex crises that affect sustainable development [2]. In recent years, many national and international organizations have launched special initiatives, for example, Green Deal, to fight against climate change and environmental degradation [2–4]. The issue of achieving climate neutrality has been on the agenda of the European Union (EU) for more than the last ten years. In order to achieve the climate goals set for 2030 and to be able to implement the EU's long-term strategy, which envisages achieving climate neutrality by 2050, it is necessary to significantly reduce carbon emissions in the EU, including in the EU's energy system [5]. The building sector is one of those

sectors where energy audits are conducted and specific goals must be achieved. One of the main directions of the European Green Deal is to prioritize energy efficiency and improve the energy performance of buildings, which will help reduce greenhouse gas (GHG) emissions and improve people's quality of life [3]. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings and Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) are of a great importance since they set basis for energy efficiency targets [6–8]. To achieve climate neutrality Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast), obligations are provided for its Member States to reach exact cumulative end-use energy savings annually from 2021 to 2030 and 2040 [4]. However, Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings sets the target of minimum energy performance standards for non-residential buildings and trajectories for progressive renovation of the residential building stock [8].

While Member States need to obtain energy consumption and its potential savings information at the comprehensive level of all its sectors, building owners, commercial operators, and service providers need to evaluate their energy consumption and possible savings. Accordingly, this is one of the energy efficiency and energy audit concept crossing points. "Namely, energy efficiency means the ratio of output of performance, service, goods or energy to input of energy [4]". However, the purpose of energy audits is obtaining adequate knowledge of the energy consumption of a building, an industrial or commercial operation, an installation, or a private or public service, and, as a result, identifying and quantifying opportunities for cost-effective energy savings, identifying the potential for cost-effective use or production of renewable energy, and reporting the findings [4]. Respectively, energy audits are instruments that provide information and suggestions to company owners, maintenance companies, homeowners, investors, various financial institutions, and other relevant parties about the energy consumption and condition of buildings, possible technical improvements, and, as a result, energy consumption reduction [9]. By using energy more efficiently and thus consuming less, all world country residents, business owners, and others can reduce their energy bills, help protect the environment, reduce climate change, improve quality of life, reduce EU dependence on imported oil and natural gas suppliers, support sustainable growth, and boost the EU and other country economies [10]. To achieve these benefits, energy efficiency must be improved on both the supply side and demand side, from production to end-use [6,8]. To move towards the goals of the Green Deal and comply with the directives, many governments have created and implemented various initiatives, regulations, and plans that provide energy efficiency-promoting measures and policies, with a focus on implementing energy management systems and conducting energy audits, as these are useful tools for increasing energy efficiency [11,12].

The aim of this review paper is to evaluate energy audit practices across EU Member States, identifying challenges and the best practices to enhance energy efficiency and move closer to achieving the EU's climate neutrality goals. The review starts with an applied methodology description (Section 2) followed by the legislative and policy framework of energy efficiency and energy audits in Section 3. Sequentially, Section 4 provides an energy efficiency performance statistical comparison in EU Member States. Further, Section 5 comprehensively describes the process of energy audits, involved parties, costs, and financing instruments. The closing sections provide a description of an energy audit case study in Latvia (Section 6), concluding that across the EU, there should be a harmonization of the types and methods of energy auditing (Section 7).

In the paper, Latvia is chosen as a case study since Latvia is one of the EU Member States obliged to reach climate neutrality and decarbonization of its building sector by 2050. As these goals cannot be reached without energy efficiency improvement measures, it is of great importance that each EU Member State's energy efficiency industry has the capacity to move the state to reaching these goals. Currently in Latvia, by January 2025, only 75 experts have active independent expert certificate status [13]. Therefore, it is necessary to bring Latvia's energy efficiency industry to light to encourage future professionals to enter the industry, as well as to a start discussion among the energy efficiency science experts on sharing experiences regarding the transposition of Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings and Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) [4,8,14].

2. Methodology

Identifying the relevant literature for this study on energy audit practices involved conducting a performance analysis on documents and journal articles published between 2009 and 2024. The bibliometric review was performed on documents published in reliable scientific publication abstract and citation databases SCOPUS and MDPI. These databases include a wide range of disciplines, provide publication metrics, and are open-access, which facilitates their use. The search focused on energy audit practices, energy efficiency measures, and associated legislative frameworks in European Union Member States.

The search was conducted using multiple queries. The selected settings for queries included searching defined keywords within titles, abstracts, and keywords of the documents; some queries also included searches in all fields or in the full text. The keywords used in the queries were enclosed in quotation marks.

The first 6 queries (see Table 1) aim to perform a search for all published documents on the topic of energy audits in the time period of 2009–2024 in the SCOPUS database. Queries 7–9 were used to perform a search for all published journal articles in the MDPI database also for the time period of 2009–2024. Query 10 was used to search for legal acts in EUROPA SEARCH, accessible from the European Commission official website's search box. For query 10, there was no time limitation.

Logical operators (AND, OR) were used in queries 1–9 to combine terms and ensure thorough results. Logical operators distinguished the use of similar keywords, particularly if a keyword has alternative terms. The logical operator AND was used in all queries in SCOPUS and MDPI, thus allowing us to find documents that refer to both energy auditing and energy efficiency, as well as allowing us to set a time restriction.

Additional gray literature was sourced from government institution websites and enterprises that offer energy audit services (company offers or websites of associations). These documents were searched in English or the Latvian language for legislative acts, and an important aspect was their validity as well as the inclusion of their amendments.

Accordingly, documents and scientific publications that did not meet the earlier mentioned criteria were not considered.

The initial search produced a wide range of the literature, which was manually screened for relevance based on title, keywords, abstract, and content. Sources were selected if they aligned with the keywords and provided insights pertinent to the study objectives. This process resulted in 84 literature sources categorized as follows:

- A total of 37 academic sources, including electronic books, scientific journals, conference papers and articles.

- A total of 40 gray studies: legislation, international standards, guidelines, technical and informative reports, and governmental guidance notes fall under this category.
- The professional use literature category collected 7 sources, such as reports on the energy market, statistical data, and websites of companies offering energy audit services [15].

Some of these references include The Odyssee and Mure databases, supported by the LIFE-CET program of the European Commission, as they were used to assess and compare energy efficiency progress by sector and country, as well as to assess national energy efficiency policy measures [16].

This study addresses a gap in energy audit research, as the existing literature is limited and lacks review articles that summarize common practices and experiences across Member States. This study contributes by consolidating existing knowledge and providing a foundation for future research in energy audit policies and practices under European Union frameworks and goals.

Table 1. Description of queries for bibliometric analysis.

No.	Query Setting	Keywords in Query	Number of Documents
		Query in SCOPUS	
1.	Advanced query in all fields, in all published documents in year range of 2009–2024	ALL ("energy audit") OR ALL ("energy auditing") AND PUBYEAR > 2008 AND PUBYEAR < 2025	9446
2.	Advanced query in title, abstract and keywords, in all published documents in year range of 2009–2024	TITLE-ABS-KEY ("Green Deal") OR TITLE-ABS-KEY ("fit for 55") AND PUBYEAR > 2008 AND PUBYEAR < 2025	3441
3.	Advanced query in title, in all published documents in year range of 2009–2024	TITLE ("energy audit") OR TITLE ("energy auditing") AND PUBYEAR > 2008 AND PUBYEAR < 2025	631
4.	Advanced query in title, in all published documents in year range of 2009–2024	TITLE ("energy audit") AND ALL ("energy efficiency") AND PUBYEAR > 2008 AND PUBYEAR < 2025	366
5.	Advanced query in title, abstract and keywords, in all published documents in year range of 2009–2024	TITLE-ABS-KEY ("Green Deal") OR TITLE-ABS-KEY ("fit for 55") AND PUBYEAR > 2008 AND PUBYEAR < 2025	321
6.	Advanced query in title, in all published documents in year range of 2009–2024	TITLE ("energy efficiency first") OR TITLE ("energy efficiency first principle") AND PUBYEAR > 2008 AND PUBYEAR < 2025	17
		Query in MDPI	
7.	Advanced query in full text field, in all published documents in year range of 2009–2024	FULLTEXT ("energy policies") AND FULLTEXT ("energy policy") AND "energy efficiency" With adding search filter for years between 2009–2024	3448
8.	Advanced query in all fields, in all published documents in year range of 2009–2024	ALL ("energy audit") OR ALL ("energy efficiency audit") AND "energy efficiency" With adding search filter for years between 2009–2024	821
9.	Advanced query in title, in all published documents in year range of 2009–2024	TITLE ("energy audit") AND ALL ("energy efficiency") With adding search filter for years between 2009–2024	23
		Query in EUROPA SEARCH	
10.	Query in all fields and all formats (Web, Word, PowerPoint, Excel, PDF)	Energy efficiency	6061

3. Legislative and Policy Framework

Energy efficiency is an important goal of many governments, aimed at reducing CO_2 emissions and obtaining a more efficient use of energy resources [17]. Although energy efficiency was not highlighted in several of the agreements and, for example, not included in the Millennium Development Goals, it later appeared in the United Nations (UN) Sustainable Development Goals, with proposals such as sustainable cities and communities, access to renewable energy and climate action, and with Sustainable Development Goal 7

calling for "international progress on energy efficiency to be doubled by 2030", and aiming "to provide universal access to reliable, modern and sustainable energy services by 2030", increasing the share of renewable energy in global energy balances and improving international cooperation on access to clean energy research and technology, including renewable energy, energy efficiency, and advanced technologies, as well as increasing investment in energy infrastructure and clean energy technologies [18]. Therefore, according to these international agreements, EU countries are required to reduce greenhouse gas emissions, not only by increasing the production and use of renewable energy, but also by using this energy more efficiently [6]. The EU has identified three main aspects for achieving its energy goals: improving energy efficiency, reducing GHG emissions, and widening the use of renewable energy resources; so, the EU governments have developed several documents related to energy and climate protection [19].

The energy efficiency policy established by the EU to reduce energy consumption and costs, as well as to reduce GHG emissions, is based on various legal acts and initiatives that bind all EU Member States. For example, the Latvian government, as one of the EU Member States, has ratified and signed several international treaties: The United Nations Framework Convention on Climate Change, the Paris Agreement, the Montreal Protocol, the Kyoto Protocol, and the UN Sustainable Development Goals [18,20–23]. The Kyoto Protocol's second article clearly states that each of the parties listed in Annex 1 is obliged to implement policies and measures that are in line with its own national circumstances, including "improving energy efficiency in key economic sectors", as well as promoting sustainable development and reducing greenhouse gas emissions [23].

Overall, a number of legislative acts, initiatives, and agreements have contributed to the development and promotion of energy efficiency (see Figure 1). Many of them have already provided a significant boost in the last century, and it is expected that this momentum will continue to grow in the coming decades.
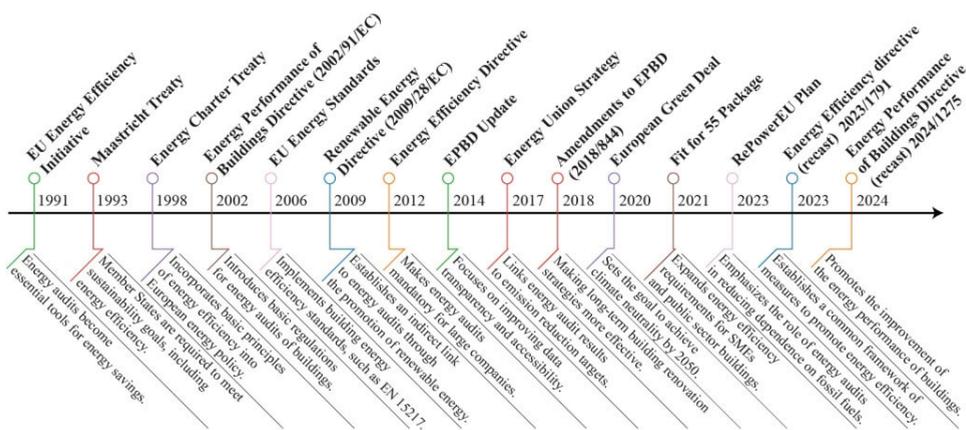
Figure 1. Historical timeline of the different energy audit promotion measures [3,4,8,24–26].

According to Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy efficiency of buildings, as amended by Directive 2018/844 of 30 May 2018 and Regulation 2018/1999 of 11 December 2018, in 2017, a long-term strategy for building renovation was developed [6,27,28]. The main goal of the strategy was to stimulate investments in the renovation of the public and private residential building stock and commercial areas, determining the improvement of energy efficiency and the renovation of multi-apartment buildings as some of the goals of housing and energy policy.

The strategy envisages appropriate, cost-effective renovation approaches for the building type and climatic zone, as well as the necessary political measures to promote building renovations [29]. It states that energy efficiency measures should be included as a key element in any strategy developed to address consumer vulnerability and energy poverty.

The directive emphasizes that improving energy efficiency strengthens energy security, lowers energy costs, and reduces GHG emissions. As energy-efficient buildings reduce the demand for heating fuel, including solid fuel, this has a positive impact on both indoor and outdoor air quality, thus contributing to EU air quality policy objectives [6,27,28].

It is also noted that improvements in energy efficiency can help achieve higher economic productivity and reduce energy poverty, thus improving the quality of life of the population. At a time when energy poverty affects around 50 million households in the EU, helping energy consumers reduce energy use in buildings can lead to lower consumer energy expenditure [30].

The directive states that, in line with the goals of the Paris Agreement, it is necessary to transform the entire EU building stock into near-zero energy buildings in the long term. However, the current volumes of building renovation are insufficient, so energy efficiency issues should be given more attention and considered as a full-fledged energy resource [8]. To facilitate the overcoming of energy efficiency obstacles, various energy policies in the form of energy programs are created in different EU countries [31].

With the Directive of the European Parliament and the Council since 2006, the EC has been paying attention to providing political support for the introduction of energy audits too. According to the European Energy Services Directive, Member States are required to implement high-quality energy audit schemes for large companies that do not have energy management systems in place, to regularly conduct energy audits, and to encourage small and medium-sized companies to conduct energy audits [6,32,33].

Energy audits and energy management systems play a key role in Article 8 of the Energy Efficiency Directive (EED) as a driver for improving energy efficiency in end-use sectors. According to the EED, Member States must promote and ensure the use of high-quality, cost-effective energy audits and energy management systems for all final consumers, including both large, small, and medium-sized enterprises (SMEs) [6].

4. Energy Efficiency Performance Comparison in EU Member States

With Commission Recommendation (EU) 2021/1749, the Energy Efficiency First (EE1) principle was established, outlining specific actions for EU countries to ensure its proper application [34].

This principle strengthens other EU objectives and has been made legally binding for Member States, requiring its application in decision-making, policy-making, investment decisions, and energy planning activities, incl. integration in national energy and climate plans (NECP) [34–37].

Valuable insights into EU countries' energy efficiency performance, enabling mutual comparison, are provided by the Odyssee-Mure database. Odyssee-Mure is a multi-year European Commission project that involves the development of an extensive statistical database (Enerdata) for key energy efficiency indicators in various economic sectors and energy efficiency policy instruments in EU Member States [38]. To evaluate how effective the EE1 principle has been integrated into the national NECPs, the quantitative indicator approach from the Odyssee and Mure databases was reviewed [16]. The indicator was applied to 14 EU Member States; this is the only database that collects indicators from at least that many Member States (see Table 1). The database employs 13 criteria (see Table 2), assessing a simple semi-quantitative scoring system ranging from 0 to 2. In this system, a score of 0 indicates non-compliance or minimal compliance, while a score of 2 reflects

a high degree of compliance. In Table 1, the column 'Total' sums up all the previously mentioned scores.

Table 2. Overview of the integration of the EE1 principle into the NECP of the countries included in the Odysee-Mure database.

Country	Total	Policy-Making Process	Removal of Barriers	Challenges	Regional and Local Level	Monitoring
Ireland	3.18	0.89	0.69	0.6	0.5	0.5
Slovenia	2.75	0.5	0.65	0.6	0.5	0.5
France	2.72	0.5	0.62	0.6	0.5	0.5
Netherlands	2.58	0.5	0.58	0	0.5	1
Spain	2.57	0.39	0.58	0.6	0.5	0.5
Latvia	2.54	0.32	0.42	0.3	0.5	1
Denmark	2.53	0.29	0.54	0.2	0.5	1
Malta	2.5	0.39	0.31	0.8	0.5	0.5
Austria	2.33	0.42	0.31	0.6	0.5	0.5
Italy	2.11	0.39	0.42	0.3	0.5	0.5
Lithuania	2.11	0.39	0.42	0.3	0.5	0.5
Poland	2.11	0.5	0.31	0.3	0.5	0.5
Sweden	1.99	0.61	0.38	0	0.5	0.5
Germany	1.98	0.29	0.69	0	0.5	0.5

All 13 criteria were grouped into five pillars:

1. Policy-Making Process (criteria: screening process, in which both supply and demand options are compared with each other, comparison between different solutions via cost–benefit analysis, discount rates, multiple benefits (MBs), and economic efficiency potentials used as a guiding principle);
2. Removal of Barriers to Energy Efficiency (criteria: prevention of distorted markets, access to information, access to capital, reduction in risk and uncertainty);
3. Tackling Energy Efficiency Challenges (criteria: energy poverty, sufficiency);
4. Integration of EE1 at regional and local level (criteria: EE1 principle on regional and local level);
5. Monitoring Energy Efficiency (criteria: monitoring) [16,39].

For comparison, Ireland, Latvia, and Germany were selected for deeper analysis. Ireland was chosen for having the highest score among the 14 participating Member States, Latvia represents a mid-range score, and Germany had the lowest score.

In Ireland, which ranks first in terms of EE1 integration, both supply-side and demand-side solutions are considered in the energy efficiency policy-making process, with the same discount rates applied for both sides. The impact of existing and planned policies is compared with the economic energy efficiency potential and financial programs that have been established to support the transition to green energy. The government uses targeted energy efficiency measures. Extensive campaigns ensure awareness of both supply-side and demand-side opportunities. However, there is no systematic approach to checking possible market imbalances and reviewing policies [16].

In Latvia, the EE1 principle has not been specifically implemented at the regional or local level. Several shortcomings exist in the energy efficiency policy: the impact of existing and planned policies is not compared with the economic energy efficiency potential, no cost–benefit analysis is conducted, and no measures have been introduced to reduce investment risks in energy efficiency, in addition to a lack of financial support. The strong point of the policy is the monitoring area, where measures are tracked depending on the sector, program, and actions. However, the monitoring would need to be enhanced by an evaluation of the overall energy efficiency progress and trends [16].

The EE1 principle has not been fully implemented in Germany either. However, comprehensive information campaigns have been developed to raise awareness of both

supply-side and demand-side options. Financial programs and funds have been established to support the transition to green energy, meaning that these instruments target not only investments in energy efficiency, but also supply-side and demand-side investments. However, no cost–benefit analysis was conducted, the same discount rates are used for supply-side and demand-side options, and there was no systematic approach to check possible market imbalances and review policies. Furthermore, no specific measures have been identified to promote energy efficiency adequacy, with information provision and awareness-raising being key enablers of the renovation policy (see Figure 2) [16].
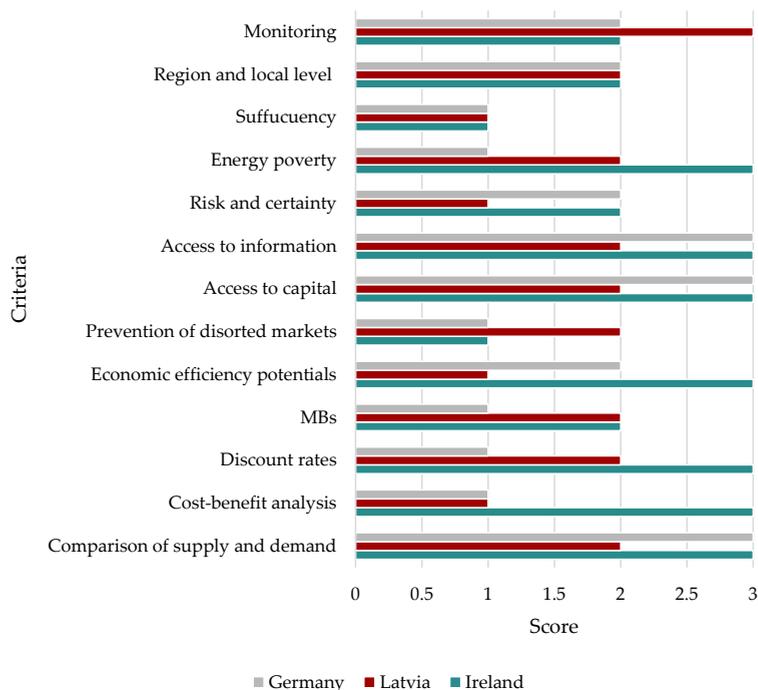
Figure 2. Evaluation of criteria in three Member States [16].

After displaying the scores of the 13 criteria, it is immediately apparent which of the criteria stagnates the assessments of all countries—these are MBs, prevention of distorted markets, and sufficiency. However, the highest scores are observed in the criteria comparison of supply and demand, as well as access to capital and information.

Ireland, as the best example, has achieved a maximum of 3 points in 7 out of 13 criteria, which significantly contributes to its top ranking, while in contrast, Germany has achieved maximum score in 3 out of 13 criteria; comparatively, Latvia has maximum score in 1 out of 13 criteria.

Despite Germany having achieved the maximum assessment in several criteria, in the remaining criteria, its assessment most often reaches only one point, which also prevents it from having a higher total score.

The European Energy Efficiency Scoreboard from the Odysee-Mure database allows for the assessment of energy efficiency performance across European countries. It is based on energy efficiency indicators from the Odysee database and information and data on policies and energy savings, relative to total energy consumption collected in the Mure database [39].

The performance of each country is analyzed through three categories: energy efficiency levels, progress, and policy indicators. Each category is scored on a scale from 0 to 1, with 1 representing the highest performance. The overall energy efficiency performance is calculated as the average score of these three categories, with each category given equal weight (one third of the total score) (Figure 3). The score reflects quantitative impact (i.e., energy savings) derived from the energy efficiency assessments.
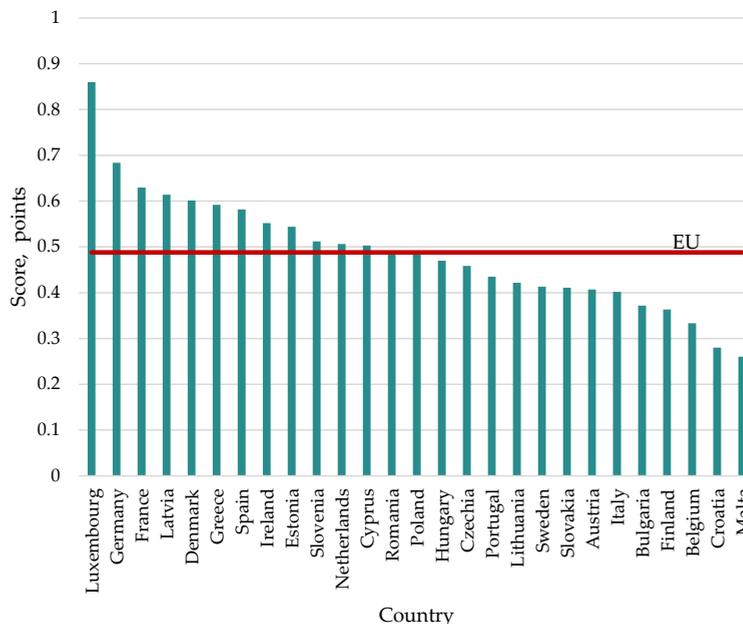
Figure 3. The overall energy efficiency performance in Member States [16,39].

The figure provides a comprehensive overview of how countries perform in energy efficiency compared to other European countries. Some countries, such as Luxembourg, Germany, and France, stand out with higher scores, indicating stronger energy efficiency performance, while several Eastern European countries (for example, Bulgaria, Lithuania, Czechia, and others) have lower scores, signaling less developed policy initiatives and slower progress in energy efficiency.

It is noted that, despite the significant promotion of interest with the help of various informative campaigns, the public's interest in participating in measures to increase energy efficiency is still at a low level, assuming that the residents mostly avoid becoming involved directly because of the large bureaucracy and many necessary administrative measures. This is linked to the need to go through extensive bureaucratic processes to receive funding from the EU structural funds, the involvement of many people by organizing general meetings of residents, and educational and explanatory events, in order to obtain the consent of the majority of the residents of the building. Often there are cases when the implementation of the energy efficiency measures of buildings is stopped because the homeowners are not interested and do not want to become involved. An undeniably significant role in the low involvement of the population is also related to the low solvency of the homeowners, debt obligations for utility payments, including for heating, the relatively long payback period of energy efficiency measures, and relatively high interest rates for financing [29,37].

5. General Overview of Energy Audits

The energy auditing of buildings or companies is a process that helps to identify problems with utility engineering in facilities, improve the comfort of the building's residents, and improve the efficiency of energy consumption in buildings and companies. In companies, energy audits also help to identify weak links in the production process, offering solutions to improve the efficiency of processes. In addition, by conducting an energy audit and analyzing the report, it is possible to evaluate the energy saving options offered. The audit process is initiated as needed, and it evaluates changes in building use, the status of utility engineering, and the applicability of new energy-efficient technologies [40]. An energy audit provides a company the opportunity to identify potential energy efficiency improvement measures and reduces energy costs [41].

Energy audits are an energy service that does not increase energy efficiency itself but is considered as an important step towards investments and energy efficiency measures. Energy audits usually are outlined in both political documents and regulatory acts as well as in the scientific literature [42,43]. Other authors point out that energy audits and energy consumption monitoring are the first steps towards increasing energy efficiency [43]. Energy audit reports can be characterized as the main component in decision-making related to energy management [44]. Energy audits are also popularized as an effective tool to promote investments in energy efficiency measures in the residential sector. Although energy audits have been operating in many countries for several decades, information on the impact of audits on the household sector is conflicting. This is related to the fact that a significant part of the energy efficiency recommendations was ignored, the main reason being that maintenance companies and homeowners considered their homes already energy-efficient enough [45].

Any energy audit process (see Figure 4) begins with the formation of an appropriate, certified energy audit team or an individual who clearly defines the scope of the audit. Before the audit begins, it is very important for the expert to review the available data to determine the duration of the audit, the costs, the size of the team (in case of companies), and to request all the necessary information about the building [40].

1	2	3	4	5
PREPARATION	**PLAN**	**PERFORMANCE**	**REPORT**	**CONCLUSION**
First meeting, determination of available information and measurement tools, definition of goals and objectives	Development of an energy audit work plan	Data collection, site survey, interviews, measurements, benchmarking, identification of energy efficiency measures	Technical and economic analysis of energy efficiency measures, report preparation, presentation of results	Development of a financing plan, securing financing, monitoring of implementation of measures, assesing results

Figure 4. The energy audit process scheme [40].

Energy audits of companies can be carried out on at least three different levels depending on the time, budget constraints, complexity of the company, and client requirements [46,47]. The basic level only provides general recommendations for energy and water savings, this type of audit does not provide long-term data analysis, while the second level provides an inspection and energy data analysis as well as recommendations for energy savings [40,47]. The most detailed is the third level, where energy consumption is finely analyzed with additional developed proposals, the priority of their implementation is

indicated, and even capital investments are indicated [47]. Regardless of the level division, the procedures of these levels are not detailed in standards or directives, leaving it to the energy audit team, which decides which data to collect and which improvements to evaluate [48].

Energy audit is especially important for historical buildings as they are energy-intensive and outdated structures, the restoration of which requires huge investments, and the improvement of buildings may sometimes be limited by the projects of individual protective zones [49]. Improving the energy efficiency of such buildings would mean environmental and financial benefits, as well as preserving cultural and historical heritage. In addition, the integration of renewable energy sources in such buildings would provide an additional influx to the energy balance of the RES of countries and reduce the use of fossil fuels [27,50].

To achieve the European Union's target of "nearly zero energy buildings", local governments have a decisive role in supporting and implementing energy-efficient measures at the local level [51].

5.1. Involved Parties of the Energy Audit

The parties involved in an energy audit can be directly or indirectly subject to the energy audit. One of the parties involved is the energy auditor (legal entity) or the independent expert who conducts qualitative and quantitative measurements of the object, selects and applies data analysis methods, conducts an inspection of the object, obtains accurate information about the existing energy consumption of the building and equipment, determines and compares the most economically efficient energy efficiency measures, determines the priorities of energy efficiency measures, and determines the possibilities of reducing CO_2 emissions [52,53]. However, primarily, they must recognize the client's wishes and develop an energy audit report (in the case of companies) and an energy-efficiency certificate (in the case of buildings) [47]. The energy audit client or customer can be a company (management or engineers), an individual (homeowner), a municipality, a state institution, or any other private or legal entities who want to carry out energy efficiency measures, determine heat losses, receive a summary of data, or receive any other benefit that can be obtained from an energy audit. They can also not benefit if they do not consider the auditor's recommendations [44].

The main audit requirements are originally set in relevant EU directives and standards, whereas the state and its institutions, based on the relevant directives and standards, provide detailed conditions for carrying out energy audits, set requirements for their performers, create a normative and institutional basis, create energy efficiency funds, provide support for research, and monitor the implementation of various projects. The functions of the EU are like those of the state—it creates regulatory acts and issues directives, and allocates and monitors various funds [49]. Employees, owners, or household members of the building/company where the audit is carried out provide access to the object, if necessary, provide information and/or analyze the data obtained, and vote for the introduction of energy efficiency measures [45,54]. Energy service companies provide access to energy services; they are employers for energy auditors and independent experts of the energy efficiency of buildings, who, in accordance with all the regulatory acts established in the state, offer their goods and professional services to consumers and ensure their availability and competitive prices. Research and educational institutions provide research and project implementation, qualified training of energy auditors, and certification [55].

5.2. Financing of Energy Audits

Financing of energy audits is an essential aspect of promoting their implementation, although energy audits provide substantial benefits, companies and other institutions are in no hurry to carry out audits due to their significantly high costs, as well as the expenses associated with necessary improvements [56]. Most commonly, municipal institutions and energy-intensive companies conduct energy audits because they are a state or municipal requirement, not due to their own initiative. Consequently, in many countries and municipalities, governments, as well as private funds, are considering ways to not only co-finance energy audits, but also provide various loan and credit options, often under favorable conditions [57,58].

In Germany, for example, to encourage small and medium-sized companies to conduct energy audits, the German Federal Ministry for Economic Affairs and Climate Action launched a Special Fund program that provided financial assistance for energy audits in small and medium-sized companies and was administered by a state-owned German institution—an investment and development bank "KfW" in cooperation with regional partners and chambers of industry and commerce. The main goal of this program was to overcome the information barriers related to the implementation of energy efficiency measures with an energy audit [59]. The provision of information and consultancy services is only covered by financial support, and the audits are carried out by independent energy auditors registered with "KfW", providing reports on the audit results, energy saving potential, and a plan for increasing energy efficiency. The daily rate of energy auditors in the amount of 60–80% was covered by the granted grants. However, only part of the proposed energy efficiency measures was used by the companies. Therefore, the German Federal Ministry for Economic Affairs and Climate Action has created two additional support mechanisms for energy-audited companies that make energy-efficient investments. One of them is a financing scheme that supports the investment of small and medium-sized companies in the field of energy-efficient technologies. The Federal Office for Economic Affairs and Export Control oversees this initiative. The other is a low-interest financing program managed by "KfW", available to companies investing in energy efficiency-related equipment. Companies have the opportunity to use both support mechanisms [60].

Energy audits are also widely used in Scandinavia—the Swedish Energy Audit Program is a state-funded program aimed primarily at small and medium-sized enterprises to help them develop and implement energy efficiency measures, incl. to finance energy audits. This program was introduced in the period from 2010 to 2014 as a tool for overcoming obstacles to energy efficiency by subsidizing energy audits of small and medium-sized industrial enterprises [31,61]. Nowadays, with the Implementation of the Energy Performance of Buildings Directive (EPBD) in Sweden, various policy instruments and supportive measures are available, including support for energy efficiency and energy audit conduction [62], offering support of up to 50% of eligible costs if the energy efficiency measure is estimated to result in the building's energy performance improved by at least 20 percent [62,63].

In Denmark, energy efficiency is one of the cornerstones of energy policy. The Danish parliament subsidized energy audits from the state budget, introducing standardized reports on heat consumption reduction measures. Since 2006, Denmark has aligned itself with the European Union's energy efficiency policy and goals. To promote energy efficiency in residential and public buildings, the Electricity Savings Trust (since 2010, the Danish Energy Savings Trust) was established. A fee paid by each electricity customer funded the trust, and several of the trust's campaigns sponsored government-subsidized personal energy audits [64]. Since 2020, Denmark has implemented the Danish Climate Agreement for Energy and Industry 2020, also providing for mandatory energy audits for large companies,

while at the same time offering a competitive subsidy scheme related to private enterprises to reduce energy consumption and CO_2 emissions [33,65,66].

5.3. Cost of Energy Audits

The industry, the size of the facility, the qualifications of the energy auditor and/or the audit company, the type of energy audit, the accuracy and completeness, the information and the data provided, and the level of competition in the auditor market, all have a significant impact on the cost of energy audits [67].

Aspects such as taxes, the general cost of living, energy costs, auditor qualifications and other factors will vary across Member States. For example, an energy audit in Germany or the United Kingdom may cost significantly more than one in Eastern Europe. Of course, some businesses choose more costly auditing methods, such as hiring a larger team, a company with more expertise, or a company with a better reputation instead of hiring an independent expert [68].

However, Table 3 presents the estimated costs of energy audits for manufacturing companies across different EU Member States. These energy audits must meet the minimum criteria outlined in Annex VI to the EU EED and any additional criteria established in national legislation transposing Article 8. These requirements ensure that audits are conducted by qualified auditors with the necessary education, skills, and experience to guarantee the quality of the audits [4].

Table 3. Price range of energy audits in 5 EU Member States in euros [68].

Country	Energy Audit Costs, Euro, for Building Area				
	<2500 m^2	2500–7000 m^2	7000–15,000 m^2	15,000–40,000 m^2	>40,000 m^2
Germany	10,000	12,000	14,000	18,000	23,000
France	9000	10,000–11,000	13,000–14,000	17,000	24,000–25,000
Italy	8000–9000	10,000	12,000–13,000	15,000–16,000	22,000–23,000
Denmark	8000	10,000	15,000	25,000	29,000
Romania	9000	17,000–18,000	21,000–22,000	22,000–23,000	250,00–27,000
Sweden	9000	11,000	16,000	27,000	32,000

It should be mentioned that the expenses listed below pertain to manufacturing companies; it cannot be excluded that an energy audit of a manufacturing company is often more time-consuming and more costly than, for example, an energy audit of an office building. The price ranges reflect the average costs for energy audits in manufacturing companies and are included solely to illustrate the price differences between Member States.

Table 3 shows the differences in energy audit costs for manufacturing sites relative to the total area occupied. As a general trend, the costs decrease as the area increases. This indicates that larger manufacturing sites do not necessarily require audits that are directly proportional to the size of the company or its energy intensity.

In general, energy audits and various energy efficiency measures are promoted all over the world, which are subsidized in various ways by companies, municipalities and countries. Despite different approaches, all these measures contribute to the reduction of CO_2 emissions, increase energy efficiency at the national and municipal level, and reduce costs related to energy consumption.

6. Case Study: Energy Audit Experience in Latvia

Latvia's national energy efficiency policy is aimed at reducing the consumption of energy resources and increasing energy efficiency in all sectors of the economy in order to achieve the energy efficiency goal set by the EU. In general, Latvia has several policies

and programs aimed at improving energy efficiency, saving energy, and reducing GHG emissions to achieve sustainable and environmentally friendly development [42,69–71].

Currently, in Latvia, energy efficiency measures and conditions for energy audits are affected and regulated by the energy efficiency law (for companies), the building energy efficiency law (for buildings), as well as other complementary regulatory acts, such as Cabinet of Ministers Regulation No. 487 "Rules for Energy Audits of Enterprises" (Figure 5) and Cabinet of Ministers Regulation No. 222 "Building energy efficiency calculation methods and building energy certification rules" [53,72].
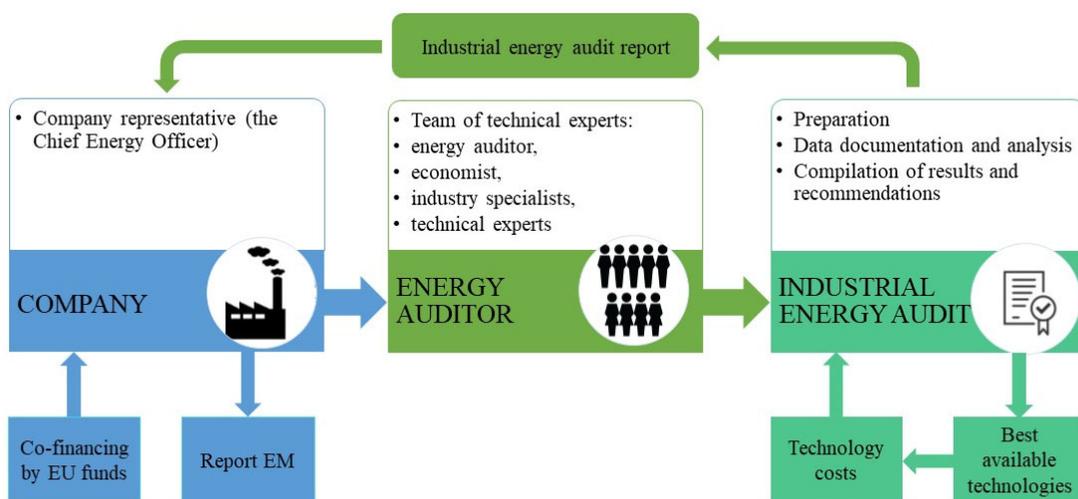
Figure 5. Steps of the industrial energy audit [41,53].

Currently, the legislators set out all the competency requirements and certification procedures for energy auditors of companies as well as independent experts of the energy certification of buildings, the monitoring and responsibility of the energy auditor and the expert, the general procedures for conducting energy audits, as well as the registration and content of an energy audit report and experts issued energy efficiency certificate of buildings in the Building Information System and the procedures for its use. Currently several companies in Latvia offer energy audit services [73].

According to the data of the State Agency "Latvian National Accreditation Bureau", there are seven institutions in Latvia whose sphere is the energy audit of companies and which comply with the requirements of LVS EN ISO/IEC 17020:2012 and are competent to carry out inspection or assessment and preparation of the report [74,75].

However, the Building Information System maintains and provides a register of all independent experts in energy efficiency of buildings field, where it is possible to obtain information about each expert, its competence area and certificate status (currently, by December 2024, 75 experts have active certificate status) [76].

In Latvia the competence of an independent expert of energy efficiency of buildings field is checked and the supervised by the Latvian Heat, Gas and Water Technologies Engineers Association, which in turn is accredited institution by Latvian National Accreditation Bureau [13].

Building energy audits are performed for all types of buildings—private houses, multi-apartment buildings, and public buildings. There is no set ceiling for the prices of energy audits, and the price of such a service depends on many factors: building size, location, type of building, scope of the audit, assigned information, and other factors [67,73]. Re-

garding the energy audit of buildings, in Latvia, there exists two kinds of energy efficiency certificates for the buildings in operation. Firstly, the energy performance certificate that is based on both calculated and measured data of energy consumption of building and a list of energy savings and energy efficiency measures is given. Secondly, the energy performance certificate that is based on measured data only. Such a certificate is especially suitable for cases where the building is being sold or rented. A list of energy savings and energy efficiency measures is not obligatory for this kind of certificate but can be added if the homeowner has demanded it. Moreover, new buildings being constructed are issued an energy efficiency certificate based on calculated data [42,77]. Since most buildings in Latvia meet the requirements of class E and F, the improvement and renovation of their energy efficiency is very urgent [77,78].

In Latvia, the Cabinet of Ministers has issued the Energy Audit Regulations for Enterprises, which determines the procedure for conducting an energy audit of enterprises, the requirements for energy auditors, the submission of reports, data reporting, and collection, and other information to be followed by all enterprise energy auditors. For insight, Figure 5 shows the scheme of the company energy audit [53].

Municipalities are also increasingly conducting energy audits of public buildings to reduce total energy consumption and mitigate substantial costs. Whether the municipality conducts energy audits for public buildings or co-finances their implementation in residential buildings may also depend on whether the municipality has obtained energy management system certification, such as ISO 50001 [79].

Several municipalities in Latvia offer the opportunity to receive co-financing for the energy audit of multi-apartment residential buildings, with a support intensity of up to 100%, for example, Talsi, city in Latvia, which offers municipal co-financing for energy audits up to 700 EUR and also up to 10,000 EUR for energy efficiency measures that were specified in the energy audit in the report [80,81].

The municipality of Liepaja also actively invites residents to use the support granted to multi-apartment residential buildings to improve energy efficiency by carrying out a series of measures, including energy audits and the renovation of buildings. In terms of the number of renovated buildings, Liepaja is the leader among cities because the implementation of energy efficiency improvement measures there has been particularly active so far. Liepaja municipality offers municipal co-financing options for the partial compensation of project documentation, develops mechanisms to facilitate formalities, which in turn makes it easier for residents to reach a common agreement, as well as invests resources in informing residents and maintenance companies [82].

Overall, in Latvia, co-financing support is available for energy audits and also energy efficiency measures for multi-apartment buildings, as well as privately owned houses. Similar approaches and support measures are available for company activities that raise the company's energy efficiency [58,83].

7. Conclusions

For more than ten years, the European Union has set increasingly higher energy efficiency targets in order to promote the energy security and energy independence of the Member States, the achievement of climate targets, and the development of a green economy. At the EU, national, and regional level, several documents have been developed that define the guidelines and goals of the energy efficiency policy, including the necessary measures to promote building renovations. Since EU Member States and other countries also have a binding obligation to reduce energy poverty, the promotion of the energy efficiency of buildings and companies is an essential tool in fulfilling the obligation. As the housing stock ages, it needs renovation measures more and more urgently. Despite

its relevance, it is not intended to establish the obligation to carry out energy efficiency measures for buildings, thus leaving the agreement on the carrying out of such measures in the voluntary control of building owners.

Unused energy efficiency improvement potential exists in many sectors of the national economy. Thus, companies participating in these programs can improve their energy efficiency, which in turn contributes to the reduction of CO_2 emissions. Energy audits are a widely recognized service, which companies and institutions often choose to use for energy efficiency purposes [45,49]. However, it is not clear whether they serve effectively for energy efficiency, since even during energy audits, there are several energy efficiency barriers—customers who do not want to invest in building or equipment renovation, data editing, object inspection, etc.—which the energy auditor or independent expert may encounter.

Research on energy audits and their connection to the legislative and policy framework confirms that there are no detailed standards and support programs that are identical across all EU Member States. To comply with the requirements of the directives, the governments of the EU Member States, including the Latvian government, have implemented various efficiency-enhancing measures and policies achieving varying levels of effectiveness. However, there are differences in how each Member State has interpreted and adapted the EU requirements, so the exchange of information between Member States based on their experience has been proposed as a key improvement aspect for countries to move together towards a Green Deal. However, it could be difficult to compare international energy audit programs because the programs are implemented and evaluated differently in each country. A combined system, such as providing information, setting goals or subsidies, can make energy audits more effective [84]. Similarly, such a system will be more effective in reducing CO_2 emissions, especially if it is combined with other policy instruments [85]. Andersson's et al. study confirms that in the evaluations of energy audit programs there are differences in both methodology and results, indicating a lack of consistency in the classification of measures [48]. For these reasons, EU countries should agree on specific but mutual types of energy audits and methods for conducting them, creating standards and manuals, and adapting them to EU climate neutrality requirements.

References

1. Pfeifer, L.; Otto, I.M. Changing seasonal temperature offers a window of opportunity for stricter climate policy. *Environ. Sci. Policy* **2023**, *140*, 35–45. [CrossRef]
2. Panarello, D.; Gatto, A. Decarbonising Europe—EU citizens' perception of renewable energy transition amidst the European Green Deal. *Energy Policy* **2023**, *172*, 113272. [CrossRef]
3. European Commission. The European Green Deal. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 12 December 2024).

4. European Parliament. *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast)*; European Union: Brussels, Belgium, 2023.

5. Kalantzis, F.; Revoltella, D. Do energy audits help SMEs to realize energy-efficiency opportunities? *Energy Econ.* **2019**, *83*, 229–239. [CrossRef]

6. Energy Efficiency Directive. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en (accessed on 17 December 2024).

7. European Parliament and of the Council. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*; European Union: Brussels, Belgium, 2010; Available online: https://eur-lex.europa.eu/eli/dir/2010/31/oj (accessed on 18 December 2024).

8. *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast) (Text with EEA Relevance)*; European Union: Brussels, Belgium, 2024.

9. Wohlfarth, K.; Eichhammer, W.; Schlomann, B.; Mielicke, U. Learning networks as an enabler for informed decisions to target energy-efficiency potentials in companies. *J. Clean. Prod.* **2017**, *163*, 118–127. [CrossRef]

10. European Commission. European Commission REPowerEU: Energy Savings and Energy Efficiency. Available online: https://ec.europa.eu/commission/presscorner/detail/en/fs_22_3137 (accessed on 6 December 2024).

11. Collombet, R.; Peillon, R.H. Energy Performance of Buildings Directive: Implementation Guide. Available online: https://efficientbuildings.eu/wp-content/uploads/2024/10/Efficient-Buildings-Europe-Implementation-Guide-2024_online-1.pdf (accessed on 9 January 2025).

12. Kubule, A.; Ločmelis, K.; Blumberga, D. Analysis of the results of national energy audit program in Latvia. *Energy* **2020**, *202*, 117679. [CrossRef]

13. Zemgale Regional Energy Agency Energy Auditors and Documents. Available online: https://www.zrea.lv/lv/eksperti_152/energoauditori_282/ (accessed on 9 December 2024).

14. European Commision. Energy Performance of Buildings Directive. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed on 20 January 2025).

15. Fox, M.; Coley, D.; Goodhew, S.; de Wilde, P. Thermography methodologies for detecting energy related building defects. *Renew. Sustain. Energy Rev.* **2014**, *40*, 296–310. [CrossRef]

16. ODYSSEE-MURE. Energy Efficiency First Tool: Benchmark & Assess the Implementation. Available online: https://www.odyssee-mure.eu/data-tools/ee1-tool.html (accessed on 16 December 2024).

17. Kanna, I.V. Energy Policies and Standards. In *Encyclopedia of Renewable Energy, Sustainability and the Environment (First Edition)*; Rahimpour, M.R., Ed.; Elsevier: Oxford, UK, 2024; pp. 9–20. [CrossRef]

18. United Nations. Sustainable Development Goals. Available online: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed on 6 December 2024).

19. European Commission. Country Report—Council Recommendation on the 2023 National Reform Programme of Latvia and Delivering a Council Opinion on the Stability Programme of Latvia. Available online: https://commission.europa.eu/system/files/2023-05/COM_2023_614_1_EN.pdf (accessed on 6 December 2024).

20. Ministry of Environmental Protection and Regional Development. Fourth National Communication of the Republic of Latvia Under United Nations Framework Convention on Climate Change. Available online: https://unfccc.int/resource/docs/natc/latnc4.pdf (accessed on 6 December 2024).

21. The Parliament of Latvia. The Paris Agreement. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=288600 (accessed on 6 December 2024).

22. Cabinet of Ministers Government of the State of Latvia. Montreal Protocol. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=34452 (accessed on 6 December 2024).

23. Government of Latvia. Kyoto Protocol. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=63180 (accessed on 6 December 2024).

24. Mauro, M.R. Energy Security, Energy Transition, and Foreign Investments: An Evolving Complex Relationship. *Laws* **2024**, *13*, 48. [CrossRef]

25. Cucchiella, F.; Condemi, A.; Rotilio, M.; Annibaldi, V. Energy Transitions in Western European Countries: Regulation Comparative Analysis. *Energies* **2021**, *14*, 3940. [CrossRef]

26. Urbano, E.M.; Kampouropoulos, K.; Romeral, L. Energy Crisis in Europe: The European Union's Objectives and Countries' Policy Trends—New Transition Paths? *Energies* **2023**, *16*, 5957. [CrossRef]

27. European Parliament. *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (Text with EEA Relevance)*; European Union: Brussels, Belgium, 2018; Volume 156.

28. European Parliament. REGULATION (EU) 2018/1999 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the Governance of the Energy Union and Climate Action, Amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and Repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. Available online: https://eur-lex.europa.eu/legal-content/LV/TXT/PDF/?uri=CELEX:02018R1999-20231120 (accessed on 9 December 2024).

29. Cabinet of Ministers Government of the State of Latvia Order of the Cabinet of Ministers no. 46: About Latvia's National Energy and Climate Plan 2021–2030. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=312423 (accessed on 9 December 2024).

30. European Commision. Energy Poverty. Available online: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-poverty_en (accessed on 9 December 2024).

31. Paramonova, S.; Thollander, P. Ex-post impact and process evaluation of the Swedish energy audit policy programme for small and medium-sized enterprises. *J. Clean. Prod.* **2016**, *135*, 932–949. [CrossRef]

32. Mbaye, A. Review on Energy Audit: Benefits, Barriers, and Opportunities. *Am. J. Energy Nat. Resour.* **2022**, *1*, 45–58. [CrossRef]

33. Dolge, K.; Kubule, A.; Rozakis, S.; Gulbe, I.; Blumberga, D.; Krievs, O. Towards Industrial Energy Efficiency Index. *Environ. Clim. Technol.* **2020**, *24*, 419–430. [CrossRef]

34. THE EUROPEAN COMMISSION COMMISSION RECOMMENDATION (EU) 2021/1749 of 28 September 2021 on Energy Efficiency First: From Principles to Practice. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021H1749 (accessed on 18 December 2024).

35. von Malmborg, F. First and last and always: Politics of the 'energy efficiency first' principle in EU energy and climate policy. *Energy Res. Soc. Sci.* **2023**, *101*, 103126. [CrossRef]

36. Mandel, T.; Pató, Z. Towards effective implementation of the energy efficiency first principle: A theory-based classification and analysis of policy instruments. *Energy Res. Soc. Sci.* **2024**, *115*, 103613. [CrossRef]

37. Cabinet of Ministers Government of the State of Latvia Latvia's National Energy and Climate Plan 2021–2030. Available online: https://energy.ec.europa.eu/system/files/2020-02/lv_final_necp_main_lv_0.pdf (accessed on 6 December 2024).

38. Thomas, S.; Rosenow, J. Drivers of increasing energy consumption in Europe and policy implications. *Energy Policy* **2020**, *137*, 111108. [CrossRef]

39. Enerdata, A. Energy Efficiency Trends & Policies | ODYSSEE-MURE. Available online: https://www.odyssee-mure.eu/ (accessed on 12 December 2024).

40. Alajmi, A. Energy audit of an educational building in a hot summer climate. *Energy Build.* **2012**, *47*, 122–130. [CrossRef]

41. TUV NORD Baltik Ltd. Energy Audit of the Enterprise—Energy Efficiency. Available online: https://www.tuv-nord.com/lv/en/services/energy-efficiency/energy-audit-of-the-enterprise/ (accessed on 16 December 2024).

42. LIKUMI.LV. Saeima the Parliament of the Republic of Latvia The Energy Efficiency Law. Available online: https://likumi.lv/doc.php?id=280932 (accessed on 9 December 2024).

43. Bunse, K.; Vodicka, M.; Schönsleben, P.; Brülhart, M.; Ernst, F.O. Integrating energy efficiency performance in production management—Gap analysis between industrial needs and scientific literature. *J. Clean. Prod.* **2011**, *19*, 667–679. [CrossRef]

44. Abdelaziz, E.A.; Saidur, R.; Mekhilef, S. A review on energy saving strategies in industrial sector. *Renew. Sustain. Energy Rev.* **2011**, *15*, 150–168. [CrossRef]

45. Murphy, L. The influence of energy audits on the energy efficiency investments of private owner-occupied households in the Netherlands. *Energy Policy* **2014**, *65*, 398–407. [CrossRef]

46. Al-Ajlan, S.A. Energy Audit and Potential Energy Saving in an Office Building in Riyadh, Saudi Arabia. *J. King Saud Univ. Eng. Sci.* **2009**, *21*, 65–74. [CrossRef]

47. Blumberga, A.; Blumberga, D.; Biseniece, E.; Kamenders, A.; Kašs, K.; Vanaga, R.; Žogla, G. *Ēku Energoefektivitāte: Vakar, Šodien un Rīt*; RTU Izdevniecība: Riga, Latvia, 2017; Available online: https://ortus.rtu.lv/zdas/lv/publications/27311 (accessed on 9 December 2024).

48. Andersson, E.; Arfwidsson, O.; Bergstrand, V.; Thollander, P. A study of the comparability of energy audit program evaluations. *J. Clean. Prod.* **2017**, *142*, 2133–2139. [CrossRef]

49. Magrini, A.; Gobbi, L.; d'Ambrosio, F.R. Energy Audit of Public Buildings: The Energy Consumption of a University with Modern and Historical Buildings. Some Results. *Energy Procedia* **2016**, *101*, 169–175. [CrossRef]

50. European Parliament. *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC Text with EEA Relevance*; European Union: Brussels, Belgium, 2012; Volume 315, Available online: http://data.europa.eu/eli/dir/2012/27/oj/eng (accessed on 9 December 2024).

51. Annunziata, E.; Rizzi, F.; Frey, M. Enhancing energy efficiency in public buildings: The role of local energy audit programmes. *Energy Policy* **2014**, *69*, 364–373. [CrossRef]

52. Moya, D.; Torres, R.; Stegen, S. Analysis of the Ecuadorian energy audit practices: A review of energy efficiency promotion. *Renew. Sustain. Energy Rev.* **2016**, *62*, 289–296. [CrossRef]

53. LIKUMI.LV. Cabinet of Ministers Government of the State of Latvia Regulations Regarding Energy Audit of Enterprises. Available online: https://likumi.lv/doc.php?id=283807 (accessed on 16 December 2024).

54. Schleich, J.; Fleiter, T. Effectiveness of energy audits in small business organizations. *Resour. Energy Econ.* **2019**, *56*, 59–70. [CrossRef]

55. Shen, B.; Price, L.; Lu, H. Energy audit practices in China: National and local experiences and issues. *Energy Policy* **2012**, *46*, 346–358. [CrossRef]

56. Kuokkanen, A.; Yazar, M. Cities in Sustainability Transitions: Comparing Helsinki and Istanbul. *Sustainability* **2018**, *10*, 1421. [CrossRef]

57. JSC Swedbank Latvia Financing. For Energy Efficiency in Apartment Buildings—With a Target of at Least 30% Primary Energy Savings. Available online: https://www.swedbank.lv/business/finance/loans/renovation (accessed on 16 December 2024).

58. Riga City Council. Binding Regulations No. RD-23-204-sn. About Municipal Co-Financing for the Renovation of Residential Buildings and Promotion of Energy Efficiency. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=342789 (accessed on 9 December 2024).

59. Schubert, T.; Breitschopf, B.; Plötz, P. Energy efficiency and the direct and indirect effects of energy audits and implementation support programmes in Germany. *Energy Policy* **2021**, *157*, 112486. [CrossRef]

60. Fleiter, T.; Schleich, J.; Ravivanpong, P. Adoption of energy-efficiency measures in SMEs—An empirical analysis based on energy audit data from Germany. *Energy Policy* **2012**, *51*, 863–875. [CrossRef]

61. Andersson, E.; Karlsson, M.; Thollander, P.; Paramonova, S. Energy end-use and efficiency potentials among Swedish industrial small and medium-sized enterprises—A dataset analysis from the national energy audit program. *Renew. Sustain. Energy Rev.* **2018**, *93*, 165–177. [CrossRef]

62. Ministry of Rural Affairs and Infrastructure Förordning (2021:664) om Stöd till Energieffektivisering i Flerbostadshus. Available online: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/forordning-2021664-om-stod-till_sfs-2021-664/ (accessed on 17 December 2024).

63. Emma Svensson, H.-O.K.H. Implementation-of-the-EPBD-in-Sweden. Available online: https://www.ca-epbd.eu/Media/638373595736227761/Implementation-of-the-EPBD-in-Sweden.pdf (accessed on 17 December 2024).

64. Sovacool, B.K. Energy policymaking in Denmark: Implications for global energy security and sustainability. *Energy Policy* **2013**, *61*, 829–839. [CrossRef]

65. ODYSSEE-MURE. Database Denmark Energy Efficiency & Trends Policies | Denmark Profile. Available online: https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/denmark.html (accessed on 17 December 2024).

66. Danish Energy Agency Få Tilskud til den Grønne Omstilling | Energistyrelsen. Available online: https://sparenergi.dk/erhvervspuljen (accessed on 17 December 2024).

67. Ltd Siltie Nami. Energy Audit. Available online: http://www.siltienami.lv/pakalpojumi/energoaudits/ (accessed on 17 December 2024).

68. Directorate-General for Energy Study on Energy Efficiency in Enterprises: Library of Typical Energy Audit Recommendations, Costs and Savings—European Commission. Available online: https://energy.ec.europa.eu/publications/study-energy-efficiency-enterprises-library-typical-energy-audit-recommendations-costs-and-savings_en (accessed on 17 December 2024).

69. Ministry of Environmental Protection and Regional Development of the Republic of Latvia Sustainable Development Strategy of Latvia Until 2030. Available online: https://www.varam.gov.lv/lv/latvijas-ilgtspejigas-attistibas-strategiju-lidz-2030gadam-latvija2030 (accessed on 6 December 2024).

70. Latvian State Language Center Informative Report—Long-Term Energy Strategy of Latvia 2030—Competitive Energy for the Society | Valsts Valodas Centrs. Available online: https://www.vvc.gov.lv/en/laws-and-regulations-republic-latvia-english/informative-report-long-term-energy-strategy-latvia-2030-competitive-energy-society (accessed on 9 December 2024).

71. Riga Energy Agency. The Riga State City Energy and Climate Action Plan of Riga for 2030. Available online: https://rea.riga.lv/wp-content/uploads/2024/03/bdf163da5b991590d5a806b580470c3204d0061b.pdf (accessed on 9 December 2024).

72. Helmane, I. New Procedure for Building Energy Certification and Energy Efficiency Calculation. Available online: https://lvportals.lv/skaidrojumi/327063-jauna-kartiba-eku-energosertifikacijai-un-energoefektivitates-aprekinasanai-2021 (accessed on 20 January 2025).

73. Ltd. "Ekodoma,". "Energoauditing," ekodoma.lv. Available online: https://www.ekodoma.lv/energoauditi (accessed on 9 December 2024).

74. Construction Control Department. Energy Audit and ISO Certification. Available online: https://www.bvkb.gov.lv/lv/energoaudits-un-iso-sertificesana (accessed on 9 December 2024).

75. Latvian National Accreditation Bureau. Accredited Institutions. Available online: https://ai.latak.gov.lv/index.php?lang=lv (accessed on 9 December 2024).

76. Construction Control Department. Building Information System: Register of Independent Experts in the Field of Energy Efficiency of Buildings. Available online: https://bis.gov.lv/bisp/lv/expert_certificates (accessed on 9 December 2024).

77. Cabinet of Ministers Government of the State of Latvia. Building Energy Efficiency Calculation Methods and Building Energy Certification Regulations. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=322436 (accessed on 17 December 2024).

78. Goverment of Latvia. Informative Report 'Long-Term Building Renovation Strategy. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=342294 (accessed on 17 December 2024).

79. International Organization for Standardization. ISO—ISO 50001—Energy Management. Available online: https://www.iso.org/iso-50001-energy-management.html (accessed on 9 December 2024).

80. Talsi County Council. Binding Regulations No. 38 About Talsi Municipality's Co-Financing for Energy Efficiency Measures in Multi-Apartment Residential Buildings. LIKUMI.LV. Available online: https://likumi.lv/doc.php?id=337803 (accessed on 9 December 2024).

81. The municipality of Talsi. Co-Financing for Energy Efficiency Measures in Multi-Apartment Residential Buildings. Available online: https://www.talsunovads.lv/lv/lidzfinansejums-daudzdzivoklu-dzivojamo-maju-energoefektivitates-pasakumu-veiksanai (accessed on 9 December 2024).

82. Liepaja County Council. Binding Regulations No. 2 About the Amount of Co-Financing of the Municipality of Liepaja and the Procedure for Its Allocation for Energy Efficiency Measures in Multi-Apartment Residential Buildings. *LIKUMI.LV.* Available online: https://likumi.lv/doc.php?id=288491 (accessed on 9 December 2024).

83. JSC Development Finance Institution ALTUM. Energy Efficiency of Apartment Buildings 2022–2026. Available online: https://www.altum.lv/en/services/individuals/energy-efficiency-of-apartment-buildings-2022-2026/ (accessed on 17 December 2024).

84. Nabitz, L.; Hirzel, S. Transposing The Requirements of the Energy Efficiency Directive on Mandatory Energy Audits for Large Companies: A Policy-Cycle-based review of the National Implementation in the EU-28 Member States. *Energy Policy* **2019**, *125*, 548–561. [CrossRef]

85. Yajima, N.; Arimura, T.H. Promoting energy efficiency in Japanese manufacturing industry through energy audits: Role of information provision, disclosure, target setting, inspection, reward, and organizational structure. *Energy Econ.* **2022**, *114*, 106253. [CrossRef]

What Drives the Circular Economy? Textile Sorting or Consumption Reduction

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Abstract

Textiles are essential in the EU's shift towards a circular economy, sustainability, and climate neutrality, accounting for 4 to 6% of the EU's ecological footprint. To explore the potential of the circular economy in the EU fashion textiles value chain, this study carried out a literature review to collect data and used system dynamics modelling to assess the potential of the circular economy. The results show that landfilling of clothing consumed and produced in the EU will increase from 3.3 million tonnes in 2018 to 5.8 million tonnes per year. Around 95% of this amount represents the lost value. The findings show that the projected increase in textile sorting capacity in the EU is insufficient to contribute to the target reduction of municipal waste streams by 2030. Moreover - sorting rates are declining. Two strategies were analysed: clothing sorting and consumption reduction. The system dynamics model led to the conclusion that it is more effective to prioritise measures aimed at reducing clothing consumption rather than focusing solely on increasing sorting capacity. However, it should be kept in mind that sorting and recycling are in any case necessary to create a circular economy. This study reduces uncertainty and knowledge gaps in the literature and can be used for policy planning.

Introduction

Textiles are among the world's oldest and most widely used artificial materials. Textiles are used not only for clothing but also in healthcare, transport, construction, and other applications [1]. Global production and consumption of textiles have doubled in the last two decades [2], with negative environmental impacts due to the textile industry's highly polluting, resource intensive, and waste generating nature. Around 87% of the fibres extracted

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from raw materials end up in landfills or are incinerated throughout their life cycle, and less than 1% are recycled back into textiles [3]. Circular economy practices are currently not widely used in the textile system and it is mostly based on a linear economic model. Nevertheless, the textile system has great potential for circularity, as most materials could be recycled or reused. Introducing the circular economy into the fashion textile value chain could result in 95% of textiles being returned to the supply chain [4].

There is an increasing number of studies on sustainability and the potential of applying the circular economy approach in the textile sector [5], which look at different aspects such as eco-labelling [6], consumer involvement [7], circular supply chain [8] and waste management [9, 10]. However, significant drawbacks can be observed: data uncertainty, outdated data or missing data. Studies reveal inconsistencies in data across different aspects, such as the global share of emissions and clothing consumption. For example, the share of emissions from the textiles sector in total global emissions ranges from 3 to 10% in the literature [1, 11, 12]. The sector also lacks up-to-date data. For example, in the EU context, the latest data on waste, emissions and resource consumption are from 2020 [13]. However, these data reflect the impact of COVID- 19, which may no longer be relevant, and several data are missing, such as the sorting rate of textiles. The next most recent data is from 2018 [14].

There is also a data gap in the literature at the time the study was conducted. In general, data are available on consumption, the share of sorted textiles and textiles entering the waste stream. The EU values are summarised in Table 1. These indicators are the most relevant for the circular economy in the textile sector. However, there is a lack of data on the amount of textiles disposed of at the production, retail and post-consumer stages in the economy chain. This is a major data gap, as information on these indicators and their projected growth provide insight into the potential of the circular economy throughout the life cycle of textiles.

There are several possible paths to achieving EU circular economy targets [15], with two primary challenges in textile system: improving sorting and recycling, and reducing consumption. The textile industry puts strong emphasis on sorting and recycling. These processes are interconnected: effective recycling requires high-quality collection and sorting, while advancements in recycling can enhance the cost-effectiveness of sorting [16].

The primary challenge with collection and sorting lies in the business model itself. The industry lacks structure and clear communication between stakeholders, which makes the system inefficient and can lead to costs that exceed revenue [17]. Sorting is mostly done manually, which leads to high labour costs. Furthermore, the quality and complex composition of textiles collected are also essential for economic viability, as these are some of the aspects that determine whether recycling will be possible [18]. Currently, most revenue comes from the resale of textiles for reuse, rather than from recycling [19].

Table 1 Key indicators of the circular economy in the textiles sector and their projections

	Baseline	Projected changes in the near future
Clothing consumption	4.38 million tonnes per year [14]	+63% [15]
Clothing lifetime	3.3 years [16]	−50% [17]
Textile sorting rate	38% [14]	+33–90 000 tonnes per year [14]
Textiles disposed of in mixed waste stream after consumption	3.3–3.7 million tonnes per year [14]	unknown

On the other hand, closed-loop recycling faces mostly technical issues, particularly when dealing with mixed fibres. Technological advancements are needed, as well as improved information on textile composition and potential contaminants [19]. Furthermore, the contamination and poor initial design of textiles can pose recycling challenges. There is also the issue of the limited number of recycling cycles, which necessitates innovative approaches [19].

The second major challenge and key driver of the textile system is consumption. In this sector, consumption is particularly unsustainable and rapidly growing. Fast fashion and overconsumption are central to the issue [20]. Fast fashion emerged when major brands capitalized by outsourcing production to lower-cost countries such as India and China [20]. This shift led to the rapid growth of production volumes, contributing to both environmental and social disruptions. Fast fashion prioritizes volume over design, quality, and product lifespan. However, unsustainable demand is the central issue.

Consumer behaviour poses a significant challenge to the adoption of sustainability and circular economy practices in the textile industry. Behaviour is complex and is influenced by multiple factors like internal aspects such as personality and motivation, and external one which include culture and social groups, situational influences such as political and economic conditions, and marketing factors like price and advertising [21]. Given this complexity, understanding and changing consumer behaviour is essential for promoting circular economy in the textile sector.

Based on the literature review, three research questions were defined: (a) What amount of clothing will be landfilled in the near future? (b) Will the increase in EU sorting capacity be sufficient to meet the objectives of the circular economy? and (c) What promotes the circular economy - sorting textiles or reducing consumption?

The aim of this study is to analyse the circular economy's potential in the fashion textiles value chain at the EU level through system dynamics modelling. Fashion textiles were chosen because they have the highest potential for a circular economy approach, based on the authors' previous research [22]. The number of landfilled textiles in the baseline scenario will be used to assess the potential of the circular economy, as this represents the lost value that could be reclaimed by implementing circular practices throughout the value chain. The results will show EU's progress towards a circular economy and sustainability and whether the EU's policy targets for textiles can be met by 2030. It will also help us understand where we need to build more momentum - by promoting sustainable consumption or improving sorting and recycling. Clearly, these aspects work hand in hand, but the aim is to understand which one needs more attention.

Methodology

Two methods were used in this study: literature review and system dynamics modelling. The literature review method was used at several stages of the study: (1) at the beginning to define the research problem; (2) to select the research method; (3) to investigate the system under study; (4) to collect data; (5) to develop policy instruments; (6) to analyse the results.

The second method chosen was system dynamics modelling. System dynamics is a research method that studies the behaviour of complex systems and the challenges they face. The aim is to analyse the structure of systems to gain a deeper understanding of their

behaviour and causes [23]. The method is commonly used by academics, large businesses, consultancies and governments to improve strategy formulation, policy development and decision-making in complex and dynamic fields [24]. It is a mathematical modelling approach. System dynamics modelling has been widely used to study value/supply chains and circular economy pathways such as reverse logistics [24, 25], closed-loop supply chain [26], recycling framework [27], material flows [28, 29], and circular economy at multiple scales [30]. The system dynamics modelling approach was chosen for this study to investigate the value chain of fashion textiles as it is suitable to look at the system structure, behaviour, interaction of elements and it is possible to create closed loop systems. Figure 1 shows the steps of the entire study and their sequence. The development of policy instruments is presented in sequence, but this does not mean that one is more important than the other or that the sequence cannot be reversed.

System Dynamics Modelling

In applying the system dynamics modelling method in this study, *Stella Architect* will be used. This software allows the creation of the system's structure and to model the system over time. The main elements of the model are stocks, flows, and parameters, which are linked to each other. The links and the interactions between the components form feedback loops. There are two feedback loops: positive driving and negative balancing loops [23]. A positive driving loop is when the connected elements change in the same direction or when an even number of elements change in the opposite direction. A negative balancing loop is when an odd number of connected components change in opposite directions.

Developing a system dynamics model involves five main steps [23]. These are problem formulation, proposing dynamics hypotheses, model formulation and simulation, model
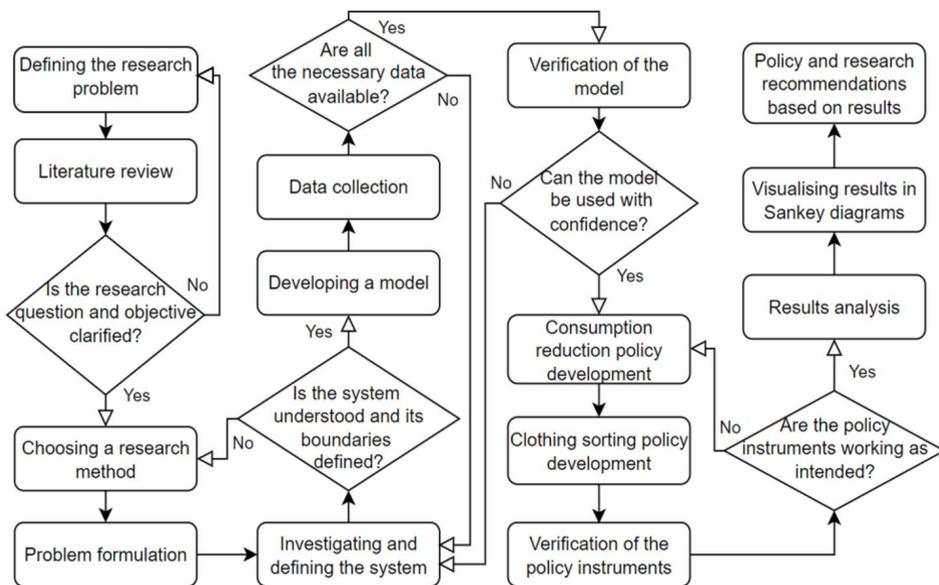
Fig. 1 Algorithm for the research methodology

testing, and policy designing and evaluation. When constructing such a model, it is common to revisit previous steps to achieve the desired results.

Problem Formulation

The first step is to define the problem and define a baseline scenario. The key dynamic problem in this study is that clothing consumption is growing rapidly while the lifespan of the product is decreasing. This has an impact on the volume of clothing landfilled and sorted. The aim of the predictive model is to forecast how much of the clothing consumed in the EU in 2030 will be landfilled and how much will be sorted.

Investigating and Defining the System

Production and export figures show that China is the world's largest producer and exporter of all textiles, while the European Union (EU) is the second largest player in the textile ecosystem [31]. Textiles play an essential role in the EU's move towards a circular economy, sustainability, and climate neutrality, being the fourth largest consumption category after food, housing, and transport regarding primary resource and water consumption and the fifth largest in greenhouse gas (GHG) emissions [32]. Textiles account for 4 to 6% of the EU's ecological footprint [33]. It is essential to underline that 76% of the GHG emissions resulting from the consumption of EU textiles are generated abroad [31]. This is because, in order to meet demand, 97% of the clothing and home textiles consumed in the EU are imported from other countries [14].

It is necessary to understand the value chain of fashion textiles to build a structure of the system. The value chain is mainly linear, from raw material extraction to the end-of-life stage [34]. There are seven main stages, interconnected by transport, except when several production steps occur in the same place. The steps are fibre extraction, yarn production, fabric production, garment manufacturing, retail of products, use phase, and end-of-life [35]. Retail also includes wholesale and distribution.

The fibre extraction stage involves the extraction and processing of fibres. Its environmental impact depends mainly on the type of raw material: artificial fibres and natural fibres. Commonly used natural fibres include cotton, wool, silk, flax, and hemp. Artificial fibres can be divided according to their polymer origin. Fibres can come from natural polymers like cellulose-based fibres (viscose, lyocell, and modal) or synthetic polymers (nylon, polyester, and acrylic) [36]. Polyester is the most widely used raw material, accounting for about half of all fibres. It should be noted that natural fibres will not necessarily have a low environmental impact. For example, it takes up to 4300 L of water to produce 1 kg of cotton [3], and this crop requires the highest amount of pesticides globally [36].

The next stage in the life cycle is the production of yarn from fibres. The thread is obtained by spinning the fibres. The spinning stage involves several mechanical processes, such as combing, smoothing, and spinning of the fibres [36]. The fibre-to-yarn stage generates waste, representing a raw material loss of around 3% [3].

Fabric manufacturing includes knitting, weaving, wet processing [37]. Wet processing involves treating yarns and fabrics using chemicals and dyes. This process generates the most significant amount of wastewater; on average, it takes about 200 L of water to produce 1 kg of fabric [36]. Worldwide, this process accounts for about 20% of all wastewater [38].

The production of textiles ends with the manufacture of the final product. At this stage, fabrics are cut and sewn to produce the desired end product [38]. Other aesthetic or functional additions are also added. The environmental impact of making the final product is relatively low [38]. However, this process generates the most textile waste of all production stages. For illustration, a study on garment production found that smaller factories generate more textile waste than larger ones, 39% and 25%, respectively [39]. These offcuts are mainly disposed of or used for energy, but the study concluded that around 50 to 80% could be recycled into new garments.

Wholesale and retail is also part of the life cycle. Globally, about 150 billion garments are produced and placed in shops annually [38]. Estimates of unsold garments vary and are reported to range from 1 to 40% [40]. Not only unsold, but also about the same amount sold at a discount [41]. Unsold and discounted textiles are often caused by fast-changing fashion, numerous new designs launched on the market and damaged goods that do not meet quality requirements [41, 42].

After production, the use phase is the second largest source of GHG emissions [38]. This is mainly due to the washing, drying, and ironing of products, which results in significant energy and water consumption [13]. Moreover, microplastic pollution is caused. Globally, around half a million tonnes of plastic microfibers are generated yearly from washing clothes. This results in ocean pollution that is 16 times higher than from the cosmetics industry [3]. These fibres come from artificial materials ranging from 64 mg per 1 kg of polypropylene to 319 mg per 1 kg of viscose [43]. The use phase and its duration is primarily up to consumers, but manufacturers also have an influence, as the quality of the textile affects the lifetime of it [44]. Consumption is growing year by year while the duration of use is decreasing. It has been projected that clothing consumption could increase by 63% by 2030 [45]. There is no specific prediction for the lifetime, but it has decreased by half over the last 15 years [33]. Globally, textile consumption is between 9 and 27 kg per person [46].

The end-of-life stage can be divided into three pathways – reuse, recycling, and incineration or disposal. First, textiles are collected separately for sorting or together with household waste. Materials collected with municipal waste are landfilled or incinerated. The share of sorted textiles varies from country to country. In the EU, 38% of textiles are separately collected, but when looking at the EU Member States individually, this fraction varies from 4.5% in Latvia to 45% in the Netherlands [14] and even up to 75% in Germany [3].

Sorted clothes are recycled or reused. Reusing textiles is more environmentally friendly than recycling [47]. Recycling can be closed-loop recycling, which is the processing of fabrics into a product that remains in the textile value chain, down-cycling, which is the reprocessing of textiles into a product that is not part of the textile value chain and has a lower added value, or up-cycling, in which a higher-value product is made [48, 49]. Upcycling is not covered in this study as it is not yet a common practise in the textile industry [50]. Closed-loop recycling is not widely used, so when recycled materials enter the textile value chain, they are most often recovered from plastic bottles [51]. This practice does not contribute to waste reduction in the textile system. Approximately 50 to 75% of the sorted textiles are reused [14]. Still, this fraction is also highly country dependent, as it is influenced by the usage habits of citizens and the sorting method applied.

Model Formulation and Simulation

Before the model is built, dynamic hypotheses are defined, during which leading stocks, flows and parameters related to the baseline behaviour are identified. Once this was done, the model was described by equations representing the relationships between the elements of the model, and the dynamic hypothesis was transformed into a computer model and updated with the other elements of the system. Initially, the main structure of the system was established, and the parts were linked by feedback before equations and input data were formulated and inserted. All input data are summarised in Annex 1. The clothing volumes were defined in tonnes, and the unit of time was a year. The specific weights were assigned a dimensionless unit. The system's structure can be divided into two parts: production and consumption of clothing and clothing after consumption. Post-consumer clothing is also split into two parts: one goes to sorting and the other to municipal waste. See Fig. 2 for the complete model.

The structure of clothing production and consumption is shown in Fig. 3. This part of the system depends on the *Specific consumption of clothing*. It influences the *Growth rate*, determining the input required to meet demand. The model cannot be used to predict clothing consumption since it increases according to *the Specific consumption growth rate*, which is a constant input into the model. In this and other parts of the model, constant parameters are marked in light blue, waste generated during production and sales is marked in dark blue, and clothing that returns to the cycle is marked in yellow.

Clothing production is divided into three parts: textile production, clothing production, and clothing sales. Textile production requires raw materials such as fibres and yarns. Textiles are further supplied to garment production, where imported textiles and closed-loop recycled garments are added. The system also accounts for exported clothing so that policy instruments influencing the share of exports can be added in future stages of model development. Clothing for sale includes garments produced after export and imported garments.
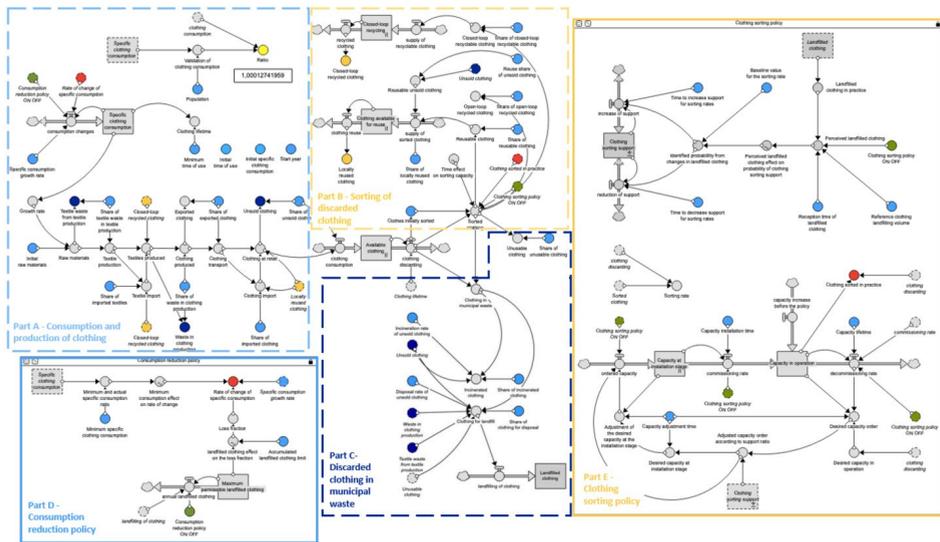
Fig. 2 Structure of a system dynamics model of the clothing value chain
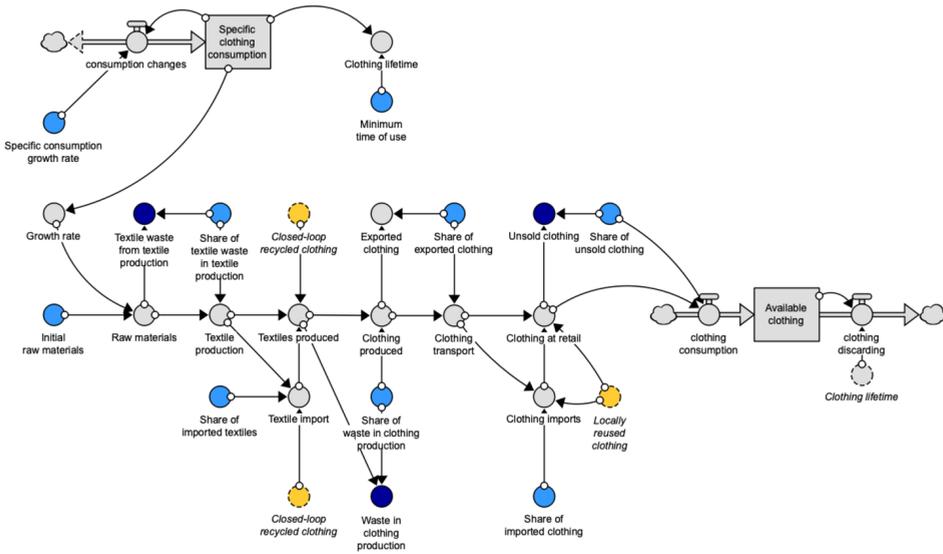
Fig. 3 Part A of the system - consumption and production of clothing

Residues are generated at all stages of production. The generation of waste in garment production outside the EU has yet to be included in the model.

After the consumer disposes of the clothes, they are sorted or put in household waste. The structure of the sorting system is illustrated in Fig. 4. This part is influenced by the *Time effect on sorting capacity*, which is the increase in projected annual capacity. The sorted garments are further divided into four streams. Clothes are reused and recycled, but there are also contaminated clothes that cannot be reused or recycled and, therefore, end up in landfill. Two types of recycling are identified: closed-loop and open-loop recycling. Additional stocks with flows have been established to create a 1/DT delay for reused and closed-loop recycled clothing. The model's time step (DT, Delta Time) is 0.25 years. The delay is created as the values of these parameters are input to the production and retail of the garment, forming circulation. All closed-loop recycled garments are assumed to return to the local value chain.

In cases where the discarded clothes do not enter the sorting stream, they end up in the municipal waste stream, see Fig. 5. Clothing from municipal waste are incinerated or landfilled. Waste from production and sales is added to this part of the system. As it is not fully known whether the production waste is also used for incineration, a worst-case scenario of all waste going to landfill was assumed. Residues from sales are incinerated or landfilled. Incineration includes energy recovery, but not necessarily.

Once the structure of the model was finalized, mathematical equations were developed to describe the relationships between the elements. For the elements represented in grey and dark blue in the model, the values are given by equations. The model includes around 70 equations, four equations that are expressed graphically and a number of additional calculations were carried out to obtain the constants used in the model.

As mentioned above, the starting part of the system depends on the specific consumption of clothing. The initial consumption of clothing per capita was obtained by dividing the overall clothing usage in the EU for 2018, which stood at 4.38 million tonnes [14], by the
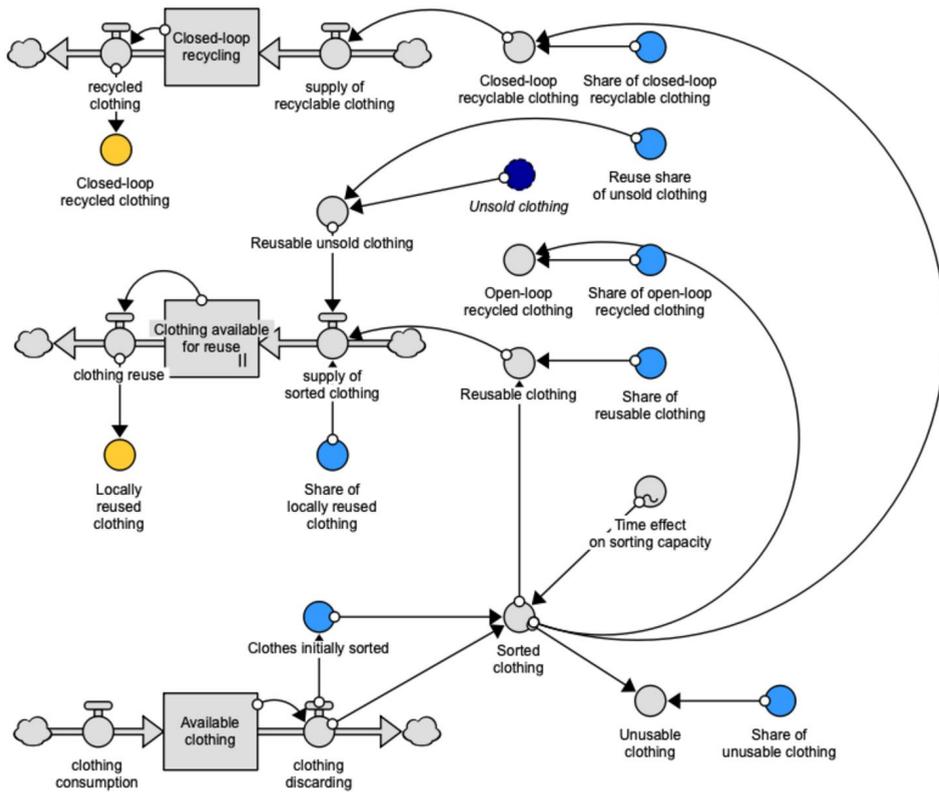
Fig. 4 Part B of the system - sorting of discarded clothing

population count of 446 million people [52]. Consequently, the clothing usage per capita was calculated to be 9.82 kg. The compound annual growth rate equation was used for the parameter, *Specific consumption growth rate*, given that clothing consumption is projected to grow by 63% by 2030 [45]. No base year was mentioned, so 2018 was assumed. The same equation was used to derive the annual reduction in clothing use time. As the time spent wearing clothes has halved over the last 15 years [33], this trend was assumed to continue until 2030 as fast fashion becomes more common and around half of fast fashion garments are worn for less than a year [3]. The initial lifetime of clothing was 3.3 years [44]. The relationship between lifetime and clothing specific consumption was expressed through a regression Eq. (1).

$$P_{lt} = 0{,}0047 \cdot S_{sc}^{-1{,}419}, \tag{1}$$

where P_{lt} is clothing lifetime (years/year) and S_{sc} is specific clothing consumption, (t/ capita)/year.

The growth rate is obtained by dividing the specific clothing consumption for a given year by the starting value for specific clothing consumption. All the parameters for clothing production depend on the *Growth rate* and the *Initial raw materials*. The initial value of the raw materials was obtained through an optimization process. The value was optimized until

Fig. 5 Part C of the system - discarded clothing in municipal waste

the specific consumption of clothing multiplied by the population in relation to the flow of clothing consumption reached a value of 1.000. The population was assumed constant as the impact of COVID- 19 on the system was not considered, and the projected population change until 2030 in the EU is not significant [53].

Sequentially, all parameters up to the stock *Clothing available* have equations based on coefficients. For example, *Textile waste from textile production* has an equation multiplying raw materials by the share of residues in production, assumed to be 0.03 [3]. Meanwhile, *Textile production* has an equation multiplying raw materials by a share of 1 - 0.03. Values such as *Closed-loop recycled clothing*, which forms the circulation in the system, were

assumed to reduce imports rather than production. For example, textile imports are calculated by Eq. (2).

$$P_{ti} = \frac{P_{tp} \cdot w_{sit}}{1 - w_{sit}} - P_{clrc}, \qquad (2)$$

where P_{ti} is textile imports (t/year), P_{tp} is textile production (t), w_{sit} is share of imported textiles and P_{scpa} is closed-loop recycled clothing (t/year).

For the stock, *Available clothing*, the initial value is obtained by multiplying the specific clothing consumption by the population and the lifetime of apparel. The quantity of clothing is multiplied by the lifetime to get an approximate amount of available clothing for use. The outflow, *clothing discarding*, is obtained by dividing the stock value by the *Clothing lifetime*.

Clothing sorting relies on *Clothes initially sorted* and *Time effect on sorting capacity*, not on the number of discarded garments, as the EU forecasts a steady increase in sorting regardless of the volume of discarded garments. The initial sorting rate was calculated by multiplying discarded garments by a 2018 sorting rate of 38% [14]. Sorting capacity increases each year based on the previous year's increase and projected capacity increase. The projected increase in textile sorting capacity from 2025 is between 45 and 90 000 tonnes per year and half of that by then [14]. *Sorted clothing* is the sum of these two factors.

The equations for the remaining parameters in the sorting part of the system are based on the product of *Sorted clothing* and the given ratios. The flow *supply of sorted clothing* is obtained by multiplying the sum of reusable and unsold clothing by the *Share of locally reused clothing*. The flow *supply of recycled clothing* equals the parameter *Closed-loop recycled clothing*. The initial stock values are the incoming flows divided by DT, as the outgoing flows are the stocks divided by DT to create a delay. The parameters associated with the outgoing flows are the same as the values of the flows.

The amount of clothing in household waste depends on the amount of sorted clothing. In the equation, sorted clothing is subtracted from discarded clothing. The parametric equations are based on the product of *Clothing in municipal waste* and the given ratio. In addition to these parameters, production, and sales waste are added and multiplied by shares. Unsold clothing is known to be reused, incinerated or landfilled [54], but its breakdown by streams in 2018 is unknown. Therefor it was assumed that 40% is incinerated, 20% is landfilled, and the rest is reused.

Data on the incineration and disposal rates of garments in the EU are unavailable, so the United States (US) figures were used. In the US in 2018, 83% of fashion textiles were landfilled, and 17% were incinerated with energy recovery [55]. This could also be the case in Europe, where large-scale recycling of textiles separated from municipal waste is unlikely due to a lack of technological solutions. As contaminated textiles are already a challenge for the recycling of sorted textiles, which are relatively cleaner than textiles that would be recoverable from municipal waste [19].

Verification of the Model

Model verification is necessary to ensure the model is complete and valid. A model can only partially be reliable, as it will never fully match the actual system, but a model can be con-

sidered reliable if it can be used with confidence. Model validation builds trust in the reliability of the model. System dynamics model verification tests fall into three groups: model structure verification tests, model behaviour verification tests, and policy impact assessment tests [56]. The model structure is assessed first, without considering the interrelationship of the elements, and only then the model behaviour is evaluated. Fourteen verification tests were conducted, including structure, parameter, and boundary adequacy (structural and behavioural) verification tests. Further tests included extreme conditions, dimensional consistency, behaviour reproduction and prediction, behaviour anomaly detection, surprise behaviour, policy extremes, and behaviour sensitivity.

Policy Development

Policymaking in a system dynamics model involves regulating flows, often by creating a new feedback loop structure or weakening or reinforcing existing feedback loops. Initially, finding the leverage points that change the behaviour of flows and stocks is necessary. There are twelve main leverage points, which are ranked according to their effectiveness. For example, the twelfth is constants, parameters, and numbers; the first is the power to transcend paradigms. The twelfth is the least effective because these leverage points rarely change behaviour in the long term, while the first is the most effective because it can break away from existing paradigms and create its unique values and priorities [57].

Two policy instruments have been developed, operating at two different leverage points. As the system is general and relatively large in scale, rather than, for example, a single textile company, the policy tools aim to show which leverage point has the most significant impact on the system's operation. The policy instruments are not based on currently planned policy measures in the EU [15].

The first policy instrument is deemed *Consumption reduction policy*. The structure of the policy instrument is based on growth and collapse. The system is shown in Fig. 6. The growth and collapse behaviour are characterized by a structure with stock that has limited capacity. The capacity signal is delayed so that when capacity is exceeded, a collapse happens, which is not followed by a recovery because a new reduced capacity has been formed [58]. However, the structure of the policy instrument developed is slightly modified, as the specific consumption of clothing stock does not have a capacity or a maximum specific consumption. The policy was therefore designed to depend on the landfilled clothing in the system.

The policy instrument applied in the model does not reflect any policy currently in practice. Still, it could be, for example, a policy to raise public awareness on the impact of textile waste and overconsumption on environment by implementing sustainability labels/logos, as the system depends on the landfilled clothing waste. A cumulative landfilled clothing limit is set, assumed to be 30 million tonnes. Each year, the landfilled clothing reduce the value of the stock. The *Landfilled clothing effect on the loss share* is a graphical representation of the impact on the loss share. The less the allowable landfill capacity left, the higher the effect on the loss fraction. The loss fraction is subtracted from the *Specific consumption growth rate*, thus reducing the specific consumption of garments.

A minimum specific consumption of 5 kg of clothing per capita has been assumed to determine the new stock capacity. When the stock value starts to approach the minimum capacity, the *Minimum consumption effect on the rate of change* approaches zero. The effect
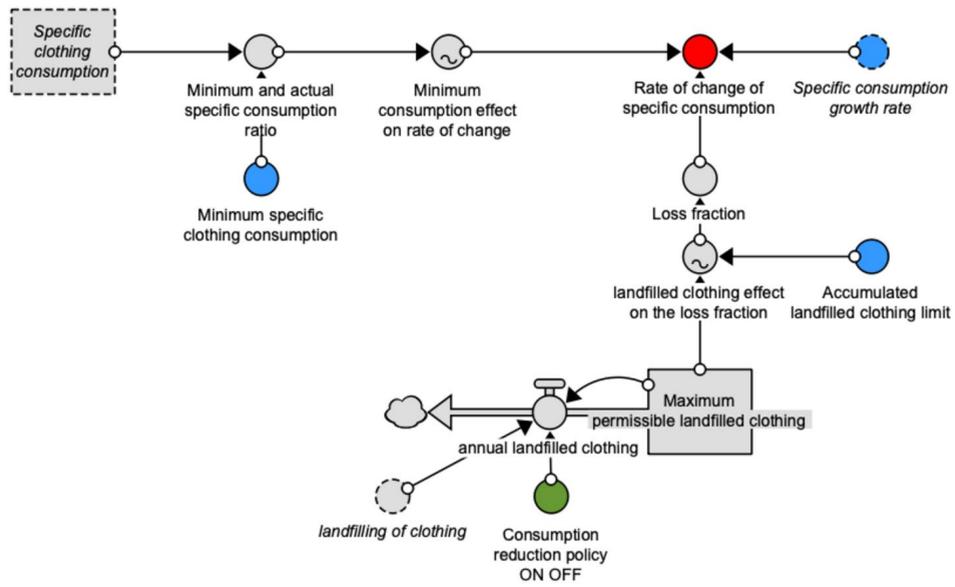
Fig. 6 Part D of the system - Structure of the consumption reduction policy

is a multiplier in the parameter *Rate of change of specific consumption*, so when it reaches zero, the change rate is also zero, and there is no change in consumption. In this scenario, sorting does not stop - the increase in sorting rates is the same as in the baseline scenario. There is just no additional increase.

The second policy instrument is the *Clothing sorting policy.* It consists of two structures. The first structure is shown in Fig. 7. It is based on the information campaign structure from the system dynamics model, which aims to predict renewable energy potential [59]. The structure is goal oriented, incorporating the information delay with the *SMTH1* function. This function forms the first order exponential smooth of input. The parameter of this function is followed by an effect that normalizes the value between 0 and 1. The effect is expressed graphically by an S-shaped curve. The probability and the time delay are set to influence the increase or decrease of the sorting support.

The structure of this policy instrument determines the intensity of support to promote the implementation of the policy in action. This support can be of any kind, such as information and financial support to waste management companies. The baseline value for the sorting rate and the reference value for the disposal rate of clothing is from 2023, as the data capture time for policy makers is assumed to be two years. The time to increase or decrease support is supposed to be three years.

To make the policy instrument more practical, an extra structure was introduced. This structure considers that sufficient sorting capacity must be available to achieve the desired sorting rate. Figure 8 illustrates this structure, which was based on the capacity structure from the bioeconomy model [60]. The bioeconomy system's production capacity depends on the available resources, but in our case, it is discarded clothes. However, this is limited by the *Clothing sorting support* because the support provided may not be enough to sort all discarded clothes. Time parameters were assumed since no in-depth literature analysis on clothing sorting was carried out. In the model, adjusting capacity takes two years, installing
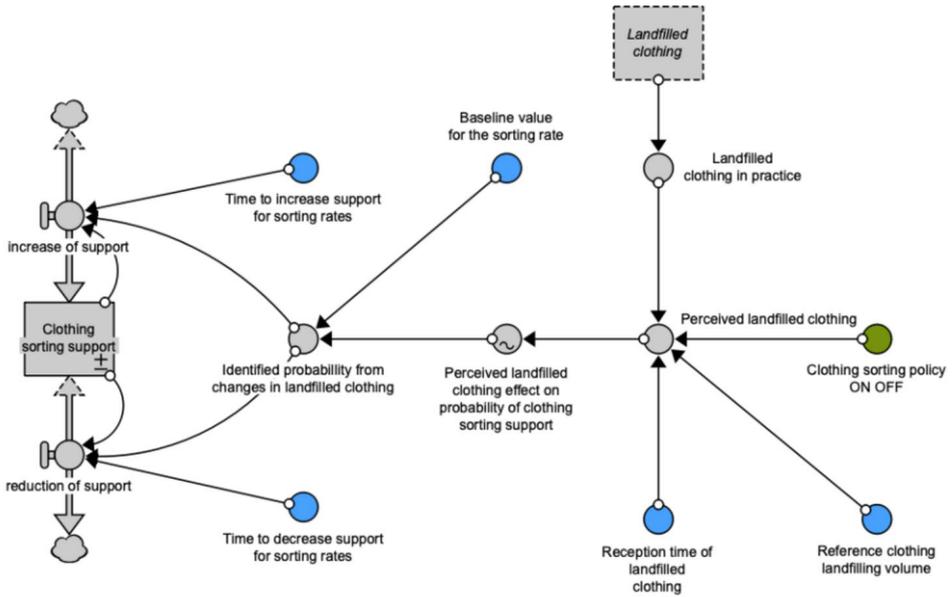
Fig. 7 Part E of the system - Structure of support for clothing sorting policy
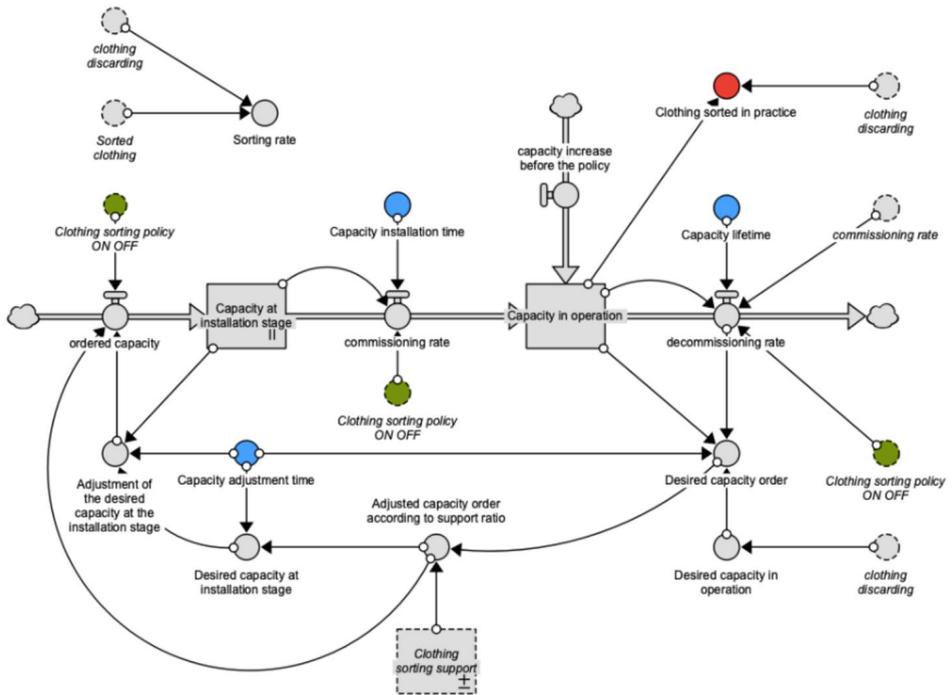
Fig. 8 Part E of the system - Structure of the capacity installation of the clothing sorting policy

it takes three, and capacity lasts ten years. Input flow was added to the *Capacity in operation* stock based on planned capacity growth each year before the policy instrument started to work. When the policy instrument becomes operational in 2025, *Clothing sorted in practice* will replace *Sorted clothing*.

Sankey Diagrams

A Sankey diagram is a visual representation of a system's links, relationships, and quantities, so it can focus the reader's attention on the essentials while keeping the system simple [61]. This method can, therefore, be used accordingly to simplify and reduce the complexity of systems. In this study, most system parameters are flows, so Sankey diagrams were created to make the results more readable. Closed loops, such as the input of reused garments from sales leftovers back into garment retail, were not displayed in the diagrams but came in as new flows. The online tool *SankeyMATIC* was used to create the diagrams.

Results

The baseline year for the model was 2018, as this was the year with the most available data. The main objective was to see how the amount of clothing landfilled will change in the near future, so the baseline scenario was modelled until 2030. In addition, four scenarios were created to look at the impact of policy instruments on the business-as-usual approach. The scenarios are summarized in Fig. 9.

Policy instruments were combined in all possible ways, resulting in four modelling scenarios. The policy instruments only start to operate in 2025, considering that past years cannot be influenced, and the EU has made the separate collection of textile waste mandatory

Fig. 9 Developed and modelled scenarios and their time intervals

Table 2 Values of key indicators of the circular economy in the textiles sector under different scenarios

	Base	Business as usual in 2030	Business as usual in 2040	With a focus on sorting clothes	With a focus on reducing consumption
Specific clothing consumption, kg/capita/year	9.8	16.0	24.1	24.1	5.0
Clothing lifetime, years	3.3	1.7	0.9	0.9	8.6
Textile sorting rate, %	38	33	31	81	100
Landfilled clothing, million tonnes/year	3.3	5.8	8.9	5.1	0.7
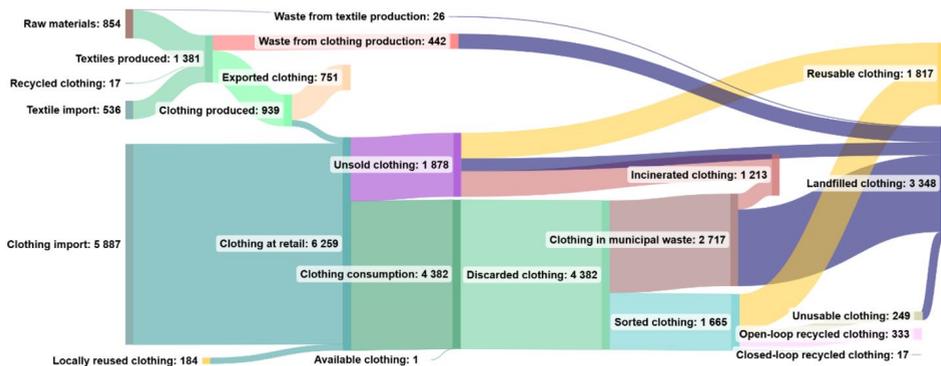
Fig. 10 Material flows in the EU fashion textiles value chain in 2018 (thousand tonnes/year)

from 2025 [15]. To give time for policy instruments to influence the model's behaviour, the simulation was extended to 2040. The first scenario is the same as the baseline scenario. In the second and third scenarios, only one of the policy instruments is activated, while in the fourth scenario both policy instruments are active. Table 2 shows the values obtained for the parameters initially defined as important indicators of the circular economy under the different scenarios. The results are described in more detail in the following subsections.

Baseline Scenario

The baseline scenario shows that 58 million tonnes of clothing consumed and produced in the EU will be landfilled from 2018 till 2030. Not all of it is landfilled in the EU because part of the textile waste is exported [18]. The model showed that in 2030, using a business-as-usual approach, clothing consumption could be 16 kg per capita, and the lifetime of clothing could decrease to 1.66 years. The estimated EU textile sorting volume in 2018 was between 1.7 and 2.1 million tonnes [14]. The initial clothing sorting in the model was 1.67 million tonnes. The results align with EU data, considering that the fraction of fashion textiles could be around 81% [14]. Figure 10 shows the results from the starting year of the simulation and the distribution of flows. All flows are shown in thousands of tonnes per year. The literature offers different versions of textile material flows in the EU, but until now no detailed overview of clothing flows was available.

The material flows in the fashion textiles value chain in the EU in 2030 are shown in Fig. 11. It can be seen that the values of all flows have increased, which is in line with the projec-

tions. As the baseline scenario included an increase in sorting capacity, the share of garment sorting was projected to increase. As shown in Figs. 10 and 11, visually, the ratio of flows has not changed significantly. The numerical value of the sorting rate also confirms this. In 2018, the clothing sorting rate was 38%, while the resulting 2030 sorting rate was 33%. The sorting rate has decreased because the identified increase in sorting capacity is proportionally lower than the increase in consumption and of discard clothing.

First Scenario – Baseline Scenario To 2040

The first scenario is the same as the baseline scenario, except that the simulation period has been extended to 2040. This is considered business as usual as the only policy included in the model is the EU's forecast for the sorting growth rate. Trends in the last ten years were assumed to be the same as up to 2030. Landfilled clothing resulted in 130 million tonnes over the years.

Second scenario – Clothing Sorting Policy

The second scenario shows a case where policy objectives in the fashion textiles value chain focus only on increasing sorting capacity. Landfilled garments reached 105 million tons from 2018 till 2040. The share of garment sorting increased to 81%.

 The activation of the clothing sorting policy created a balancing loop, which can be seen in Fig. 12. The figure shows only the most relevant elements of the causal loop. The first link states that, as the volume of clothes deposited in landfills increases, the proportion of support for sorting also increases. The higher the sorting support, the higher the sorting capacity in operation, equal to the sorted clothes. A balancing loop is created because the volume of clothes sorted increases, and the volume of clothes in municipal waste decreases.

Third scenario – Consumption Reduction Policy

The third scenario is where policy objectives in the fashion textiles value chain focus only on reducing clothing consumption. The policy instrument weakens the positive loop between specific clothing consumption and consumption change. Landfilled garments amounted to 71 million tonnes over the period considered. A significantly higher reduction than in the
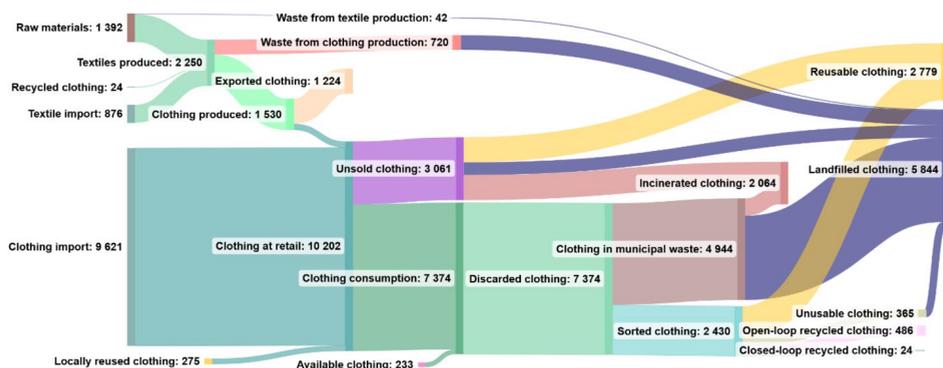
Fig. 11 Material flows in the EU fashion textiles value chain in 2030 (thousand tonnes/year)
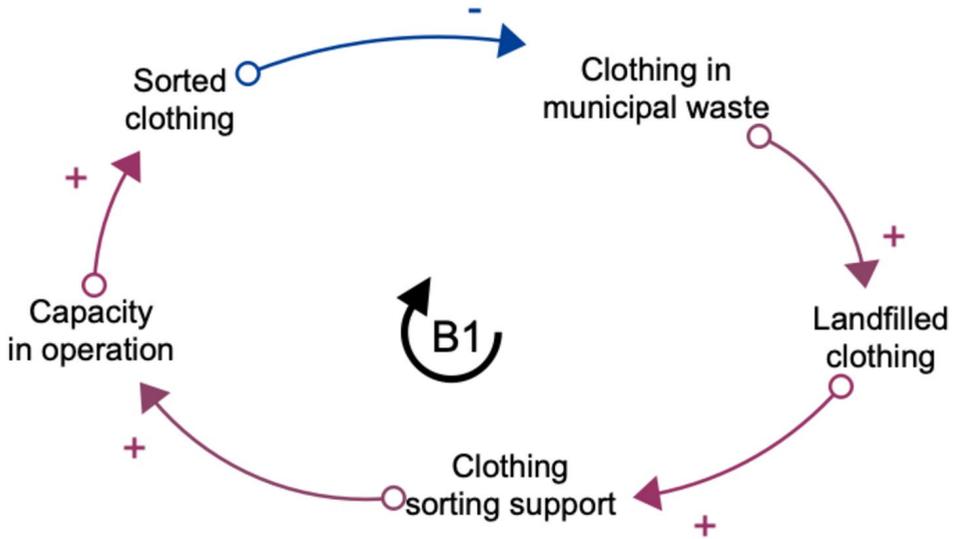
Fig. 12 Causal loop diagram for clothing sorting policy

second scenario (Clothing sorting policy) is achieved, and clothes are fully sorted in 2033, as the increase in sorting capacity in the baseline scenario is sufficient to ensure the complete sorting of discarded clothes.

The behaviour of the stock, *Specific consumption of clothing*, was predicted to increase with overshooting and a collapse. The resulting behaviour was in line with the predictions. Clothing consumption reached 14.5 kg per capita in 2028 and then declined sharply to 5 kg per capita, set as the minimum value.

The launch of the policy to reduce clothing consumption created two balancing loops, as shown in Fig. 13. The key element is specific clothing consumption, which depends on the amount of landfilled clothing in the case of a policy instrument. In the large negative loop, the first link states that the maximum available quantity of landfilled clothing decreases as landfilling of clothing increases. The lower the amount of clothes that are discarded in the fashion textiles value chain, the greater the effect on the loss fraction, which reduces the specific consumption of clothing. The specific consumption of the garment determines the amount of landfilled clothing. In addition, a balancing loop is formed, which stabilizes specific clothing consumption when it has decreased.

Fourth scenario – Consumption Reduction Policy and Clothing Sorting Policy

Both policy instruments were activated in the fourth scenario, thereby all three causal loops described above were active. This scenario is the best, as landfilled garments reached 68 million tonnes, half the level of the first baseline scenario to 2040.

All clothes will be sorted by 2032. Results show that sorted clothing, once it reaches a sorting rate of "1", follows the behaviour of discarded clothing, as it is not possible to sort more clothing than is discarded. This results in unused installed sorting capacity as it cannot adapt as quickly to the reduction in discarded clothing. This excess capacity can be used to sort other textile products.
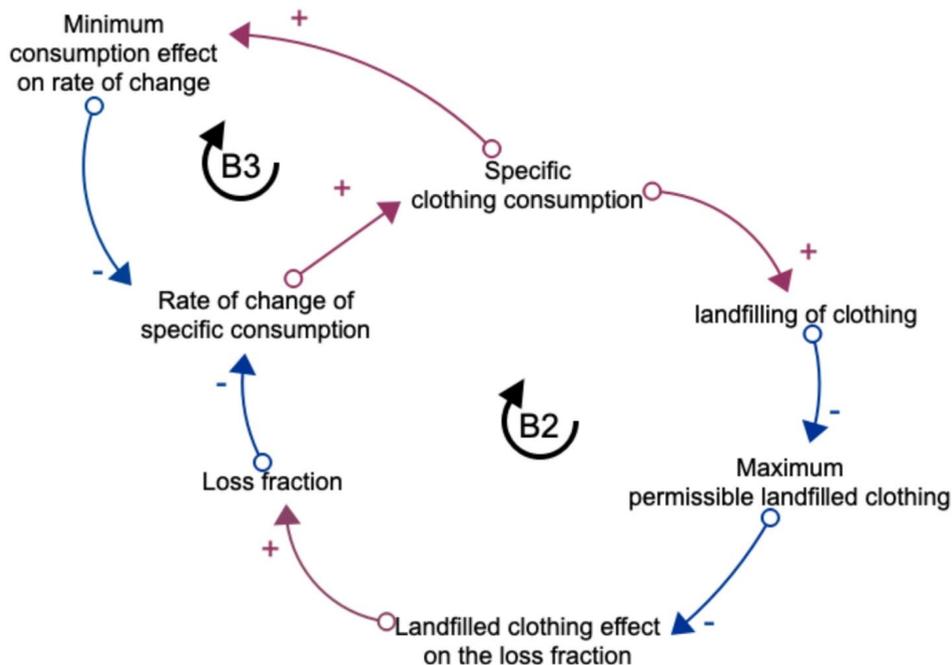
Fig. 13 Causal loop diagram of policy to reduce clothing consumption

A comparison of the behaviour of the scenarios is shown in Fig. 14. The best scenario is the fourth one. At the same time, the most effective policy instrument is the *Consumption Reduction Policy*, as it follows the same trend as scenario 4. This is also the preferred baseline behaviour: the amount of clothing landfilled starts to increase much more slowly, but it still increases slightly because the sorted clothing stream also contains contaminated clothing that cannot be recycled or reused, and the scenarios do not consider the reuse, recycling or avoidance of production and sales leftovers, which also affects the landfilled textile amount.

The flows in 2040 resulting from the fourth scenario are shown in Fig. 15. There is no municipal waste stream, but landfilling of clothing still takes place. The most significant flow at the end of the value chain is reused clothing. The Sankey diagram also points to other pressing issues that need attention, such as the export of second-hand clothing and its lack of domestic use, the landfilling of industrial and commercial waste and the still very low share of closed-loop recycling. As before, the flows are shown in thousand tonnes per year.

Conclusions

The findings provided answers to all the research questions posed. The first question was "How much clothing will be landfilled in the near future?" The system dynamics model showed that between 2018 and 2030, 58 million tonnes of clothing produced and consumed
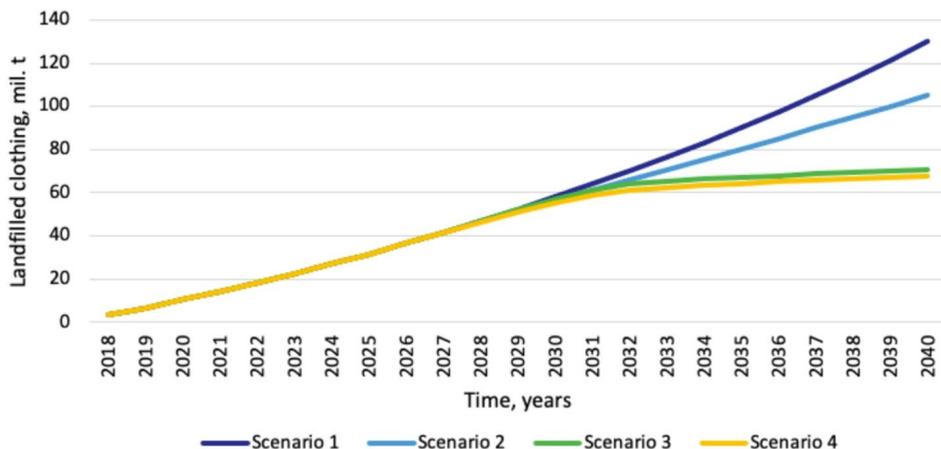
Fig. 14 Comparison of changes in baseline behaviour in the modelled scenarios
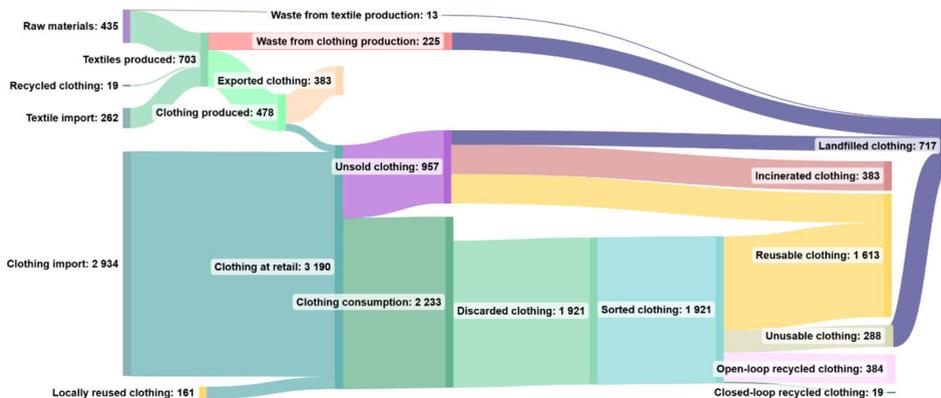
Fig. 15 Material flows in the EU fashion textiles value chain in 2040 from Scenario 3 and 4 (thousand tonnes/year)

in the EU will be landfilled. Theoretically, around 95% of this amount represents the lost value that could be recovered if a circular economy were introduced into the value chain.

The next research question was "Will the increase in EU sorting capacity be sufficient to meet the circular economy objectives?" The projected increase in textile sorting capacity was between 45 and 90 thousand tonnes per year from 2025 and half that by then [14]. The model included the highest projected capacity increase without considering that it was projected for the whole textile stream. From the results, it can be concluded that the projected capacity increase is insufficient to contribute to a level of 60% recycling in the municipal waste stream by 2030 [4]. In the baseline scenario, the sorting rate even decreased compared to 2018.

And the final question was "What promotes the circular economy - sorting textiles or reducing consumption?" A comparison of the scenarios shows that the fourth scenario, with *Clothing sorting policy* and *Consumption reduction policy* working, is the best. However, the most effective policy instrument is the *Consumption Reduction Policy*. The clothing

reduction strategy reduces annual waste landfill by almost 80% compared to the baseline situation. Consumption of clothing has reduced and stabilised at 5 kg per capita and with a lifetime of almost 9 years. This strategy has also achieved 100% sorting capacity. In this scenario, the EU sorting growth rate is sufficient as consumption declines. Therefore, it should be kept in mind that sorting and recycling are in any case necessary to create a circular economy.

In this study, material flows in the EU textile system are presented in Sankey diagrams, thus reducing the data uncertainty in the literature. Lastly, in order to address the knowledge gap on textile landfilling, it was mathematically modelled that, in the baseline scenario, the volume of fashion textiles is likely to be 3.3 million tonnes per year and in the following years it will reach 5.8 million tonnes per year.

The results can be used to improve textile circular economy strategies and policies. The model showed that the planned increase in sorting capacity is only sufficient if additional pressure is put on other drivers. The results indicated that it is more effective to prioritize actions aimed at reducing clothing consumption rather than focusing exclusively on increasing sorting capacity. Additional areas of concern requiring attention and further research were also highlighted, such as the export of used clothing and textile waste, the lack of local reuse, the recycling potential of production and retail waste and the necessity to promote closed-loop recycling. However, it should be noted that due to data limitations, several assumptions were made in the model that could have affected the results. The assumptions are covered in the methodology section.

This paper outlines the fashion textile value chain in the EU. Aspects of interest and relevance can be further explored using the developed system dynamics model as a basis. The model can be adapted to various settings by changing the input data, for example to simulate smaller scales such as a country. The model also could be expanded with policy instruments reflecting policies in practice or planned. They could be incorporated into the model in the same way as the policy instruments introduced in this study. However, they could be more detailed and reflect actual practice. Furthermore, environmental or socio-economic parameters could also be included in the model. For example, the environmental impacts could have been considered by complementing the model with a life cycle analysis study. Or the inclusion of social factors, such as the jobs created by increased sorting capacity. And also, economic factors, for example by modelling an Extended Producer Responsibility system and assessing what the economic benefits would be.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

1. Yasin S, Sun D (2019) Propelling textile waste to ascend the ladder of sustainability: EOL study on probing environmental parity in technical textiles. J Clean Prod 233:1451–1464. https://doi.org/10.1016/J.JCLEPRO.2019.06.009
2. Shirvanimoghaddam K, Motamed B, Ramakrishna S, Naebe M (2020) Death by waste: fashion and textile circular economy case. Sci Total Environ 718:137317. https://doi.org/10.1016/J.SCITOTENV.2020.137317
3. Ellen MacArthur Foundation (2017) A new textiles economy: Redesigning fashion's future
4. Juanga-Labayen JP, Labayen IV, Yuan Q (2022) A review on textile recycling practices and challenges. Text 2(1):174–188. https://doi.org/10.3390/TEXTILES2010010
5. Jia F, Yin S, Chen L, Chen X (2020) The circular economy in the textile and apparel industry: A systematic literature review. J Clean Prod 259:120728. https://doi.org/10.1016/J.JCLEPRO.2020.120728
6. Ranasinghe L, Jayasooriya VM (2021) Ecolabelling in textile industry: A review. Resour Environ Sustain 6:100037. https://doi.org/10.1016/J.RESENV.2021.100037
7. Wagner MM, Heinzel T (2020) Human perceptions of recycled textiles and circular fashion: a systematic literature review. Sustain 12(24):10599. https://doi.org/10.3390/SU122410599
8. Saccani N, Bressanelli G, Visintin F (2023) Circular supply chain orchestration to overcome circular economy challenges: an empirical investigation in the textile and fashion industries. Sustain Prod Consum 35:469–482. https://doi.org/10.1016/j.spc.2022.11.020
9. Zandberga A, Kalnins SN, Gusca J (2023) Decision-making algorithm for waste recovery options. Review on textile waste derived products. Environ Clim Technol 27(1):137–149. https://doi.org/10.2478/rtuect-2023-0011
10. Chowdhury NR, Paul SK, Sarker T, Shi Y (2023) Implementing smart waste management system for a sustainable circular economy in the textile industry. Int J Prod Econ 262:108876. https://doi.org/10.1016/j.ijpe.2023.108876
11. Patwary S (2020) Clothing and textile sustainability: current state of environmental challenges and the ways forward. Text Leather Rev 3(3):158–173. https://doi.org/10.31881/TLR.2020.16
12. Imran S et al (2023) Assessing the potential of GHG emissions for the textile sector: a baseline study. Heliyon 9(11):e22404. https://doi.org/10.1016/j.heliyon.2023.e22404
13. European Environment Agency. Textiles and the environment: the role of design in Europe's circular economy. Accessed 13 Feb 2025. [Online]. Available: https://www.eea.europa.eu/publications/textiles-and-the-environment-the
14. Köhler A et al (2021) Circular economy perspectives in the EU textile sector. Publications Office Eur Union Luxembourg. https://doi.org/10.2760/858144
15. European Commission. EU strategy for sustainable and circular textiles. Accessed 13 Feb 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0141
16. Brieger IM, Jarmer J-P, Muschkiet M (2021) Coping with challenges of textile collection through an innovative framework towards a sustainable textile circular economy. Univ Limerick. https://doi.org/10.31880/10344/10167
17. Karell E, Niinimäki K (2019) Addressing the dialogue between design, sorting and recycling in a circular economy, Des. J22(sup1):997–1013. https://doi.org/10.1080/14606925.2019.1595413

18. Boschmeier E, Ipsmiller W, Bartl A (2024) Market assessment to improve fibre recycling within the EU textile sector. Waste Manag Res J Sustain Circ Econ 42(2):135–145. https://doi.org/10.1177/0734242X231178222

19. McCauley E, Jestratijevic I (2023) Exploring the business case for textile-to-textile recycling using post-consumer waste in the us: challenges and opportunities. Sustain 15(2):1473. https://doi.org/10.3390/su15021473

20. Binet F, Coste-Manière I, Decombes C, Grasselli Y, Ouedermi D, Ramchandani M (2019) Fast fashion and sustainable consumption. In S. S. Muthu (ed) Fast fashion, fashion brands and sustainable consumption, in Textile Science and clothing technology, Singapore: Springer Singapore, pp. 19–35. https://doi.org/10.1007/978-981-13-1268-7_2

21. Zhang B, Zhang Y, Zhou P (2021) Consumer attitude towards sustainability of fast fashion products in the UK. Sustainability 13(4):1646. https://doi.org/10.3390/su13041646

22. Valtere M, Bezrucko T, Blumberga D (2023) Analysis of textile circularity potential. Environ Clim Technol 27(1):220–232. https://doi.org/10.2478/RTUECT-2023-0017

23. Duggan J (2016) An Introduction to System Dynamics. In System dynamics modeling with R, in lecture notes in social networks, Springer, Cham, pp. 1–24.. Available: https://doi.org/10.1007/978-3-319-34043-2_1

24. Alamerew YA, Brissaud D (2020) Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries. J Clean Prod 254:120025. https://doi.org/10.1016/j.jclepro.2020.120025

25. Kazancoglu Y, Ekinci E, Mangla SK, Sezer MD, Kayikci Y (2021) Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics. Bus Strategy Environ 30(1):71–91. https://doi.org/10.1002/bse.2610

26. Franco MA (2019) A system dynamics approach to product design and business model strategies for the circular economy. J Clean Prod 241:118327. https://doi.org/10.1016/j.jclepro.2019.118327

27. Kuo T-C, Hsu N-Y, Wattimena R, Hong I-H, Chao C-J, Herlianto J (2021) Toward a circular economy: A system dynamic model of recycling framework for aseptic paper packaging waste in Indonesia. J Clean Prod 301:126901. https://doi.org/10.1016/j.jclepro.2021.126901

28. Gao C, Gao C, Song K, Fang K (2020) Pathways towards regional circular economy evaluated using material flow analysis and system dynamics. Resour Conserv Recycl 154:104527. https://doi.org/10.1016/j.resconrec.2019.104527

29. Lähdesmäki S, Hanski J, Huttunen-Saarivirta E (2023) Insights into circular economy potential of lithium by system dynamic modelling of material streams. Batter. Supercaps 6(12): e202300231. https://doi.org/10.1002/batt.202300231

30. Guzzo D, Pigosso DCA, Videira N, Mascarenhas J (2022) A system dynamics-based framework for examining circular economy transitions. J Clean Prod 333:129933. https://doi.org/10.1016/j.jclepro.2021.129933

31. European Commission, Directorate-General for Internal Market, Industry, and Entrepreneurship and SMEs (2021) Data on the EU textile ecosystem and its competitiveness: final report. Publications Office of the European Union [Online]. Available: https://doi.org/10.2873/23948

32. European Commission. A new circular economy action Plan. Accessed 13 Feb 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386%26;uri=COM:2020:98:FIN

33. Šajn N (2022) Textiles and the environment. European Parliamentary Research Service. Accessed 13 Feb 2025. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729405/EPRS_BRI(2022)729405_EN.pdf

34. Braun G, Som C, Schmutz M, Hischier R (2021) Environmental consequences of closing the textile Loop—Life cycle assessment of a circular polyester jacket. Appl Sci 11(7):2964. https://doi.org/10.3390/app11072964

35. Wetterberg K, Barrie J, Schröder P, House C (2022) The EU'S circular economy transition for plastics and textiles: opportunities and challenges for trade partners in emerging markets

36. Karthik T, Gopalakrishnan D (2014) Environmental Analysis of Textile Value Chain: An Overview. In Roadmap to Sustainable Textiles and Clothing, in Textile Science and Clothing Technology. Springer, Singapore, pp 153–188. [Online]. Available: https://doi.org/10.1007/978-981-287-110-7_6

37. Madhav S, Ahamad A, Singh P, Mishra PK (2018) A review of textile industry: wet processing, environmental impacts, and effluent treatment methods. Environ Qual Manag 27(3):31–41. https://doi.org/10.1002/tqem.21538

38. Jana P (2022) Challenges in the traditional fashion and textile supply chain. In Lean Supply Chain Management in Fashion and Textile Industry, in Textile Science and Clothing Technology. Springer, Singapore, pp 31–45. [Online]. Available: https://doi.org/10.1007/978-981-19-2108-7_2

Springer

39. Aus R, Moora H, Vihma M, Unt R, Kiisa M, Kapur S (2021) Designing for circular fashion: integrating upcycling into conventional garment manufacturing processes. Fash Text 8(1):1–18. https://doi.org/10.1186/S40691-021-00262-9/FIGURES/7

40. European Environment Agency (,) The destruction of returned and unsold textiles in Europe's circular economy. LU: Publications Office. Accessed 28 Feb 2025. [Online]. https://data.europa.eu/doi/10.2800/109430

41. Wulff G (2024) The challenge of overproduction and overconsumption. In: Bäckström K, Egan-Wyer C, Samsioe E (eds) in The future of consumption. Springer International Publishing, Cham, pp 205–223. doi: https://doi.org/10.1007/978-3-031-33246-3_13.

42. Unsold clothes: why the ban on their destruction will also have perverse effects #672," PARIS GOOD fashion. Accessed 13 Feb 2025. [Online]. Available: https://parisgoodfashion.fr/en/news/unsold-clothes-why-the-ban-on-their-destruction-will-also-have-perverse-effects-672/

43. Hann S, Sherrington C, Jamieson O, Hickman M, Kershaw P, Bapasola A (2018) Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. [Online]. Available: https://eunomia.eco/reports/investigating-options-for-reducing-releases-in-the-aquatic-environment-of-microplastics-emitted-by-products/

44. Cooper T, Claxton S (2022) Garment failure causes and solutions: slowing the cycles for circular fashion. J Clean Prod 351:131394. https://doi.org/10.1016/J.JCLEPRO.2022.131394

45. Manshoven S, Christis M, Vercalsteren A, Arnold M (2019) Textiles and the environment in a circular economy. European Topic Centre Waste and Materials in a Green Economy

46. Manshoven S, Smeets A, Arnold M, Mortensen LF (2021) Plastic in textiles: potentials for circularity and reduced environmental and climate impacts. [Online]. Available: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts

47. Semba T, Sakai Y, Ishikawa M, Inaba A (2020) Greenhouse gas emission reductions by reusing and recycling used clothing in Japan. Sustainability 12(19):8214. https://doi.org/10.3390/su12198214

48. Huang X et al (2024) Industrialization of open- and closed-loop waste textile recycling towards sustainability: A review. J Clean Prod 436:140676. https://doi.org/10.1016/j.jclepro.2024.140676

49. Sandin G, Peters GM (2018) Environmental impact of textile reuse and recycling – A review. J Clean Prod 184:353–365. https://doi.org/10.1016/j.jclepro.2018.02.266

50. Kamble Z, Behera BK (2021) Upcycling textile wastes: challenges and innovations. Text Prog 53(2):65–122. https://doi.org/10.1080/00405167.2021.1986965

51. Hornbuckle R, Goldsworthy K, Knight L (2023) A systemic material innovation study of the current state and future possibilities for circular polyester. Sustainability 15(12):9843. https://doi.org/10.3390/su15129843

52. Eurostat. Population change - demographic balance and crude rates at national level. Accessed 13 Feb 2024 [Online]. Available: https://doi.org/10.2908/DEMO_GIND

53. Eurostat. Short-term update of the projected population (2022–2032). Accessed 13 Feb 2025. [Online]. Available: https://doi.org/10.2908/DEMO_GIND

54. Cybis P, Bernard S (2021) Fast fashion: why firms incinerate deadstock, and public policies. Smart Prosperity Institute, [Online]. Available: https://institute.smartprosperity.ca/sites/default/files/Fashion_WP_report.pdf

55. United States Environmental Protection Agency. Nondurable Goods: Product-Specific Data. Accessed 13 Feb 2025. [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/nondurable-goods-product-specific-data#ClothingandFootwear

56. Bala BK, Arshad FM, Noh KM (2017) Tests for confidence building. In System dynamics, in Springer Texts in business and economics. Singapore: Springer Singapore. pp 133–148. https://doi.org/10.1007/978-981-10-2045-2_6

57. Egerer S, Cotera RV, Celliers L, Costa MM (2021) A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. Agric Syst 189:103052. https://doi.org/10.1016/j.agsy.2021.103052

58. Duggan J (2016) Modeling limits to growth. In System dynamics modeling with R, in lecture notes in social networks. Springer International Publishing, Cham, pp 49–71. https://doi.org/10.1007/978-3-319-34043-2_3

59. Pakere I, Kacare M, Grāvelsiņš A, Freimanis R, Blumberga A (2022) Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia. Smart Energy 7:100081. https://doi.org/10.1016/J.SEGY.2022.100081

60. Blumberga A, Bazbauers G, Davidsen PI, Blumberga D, Gravelsins A, Prodanuks T (2018) System dynamics model of a biotechonomy. J Clean Prod 172:4018–4032. https://doi.org/10.1016/J.JCLEPRO.2017.03.132

61. Schmidt M (2008) The Sankey diagram in energy and material flow management: part II: methodology and current applications. J Ind Ecol 12(2):173–185. https://doi.org/10.1111/j.1530-9290.2008.00015.x

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Bioeconomy Towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps

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Abstract – **The rapid consumption of resources, as well as the increase in the number of people, has raised awareness of the urgent need to change Europe's existing methods and attitudes towards the consumption of biological resources in production, processing, storage, reuse and disposal. One of the key principles of the European Green Deal is to make the EU economy sustainable. Achieving this goal requires promoting resource efficiency through the transition to a clean circular economy, restoring biodiversity and, above all, reducing pollution in order to mitigate climate change. The aim of the research is to create and offer bioeconomy opportunities, by demonstrating, analysing, and describing possible solution with the help of various examples. In order to compare different production process methods, which helps to understand which of them best meets the set sustainability criteria, fuzzy cognitive maps (FCM) modelling method was used. Alternatives to 16 bio-products are evaluated using the FCM (fuzzy cognitive maps) method using the Mental Modeller tool, according to four criteria – environmental, economic, social and technological aspects. Obtained results are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate to compare the various alternative production processes considered in the work.**

Keywords – **Bioproducts; fuzzy cognitive maps (FCM); resources; sustainability**

1. INTRODUCTION

Mankind continues to consume natural resources and services unsustainably, exceeding the rate at which these resources can multiply, regenerate, and renew, in that way increasing pressure on climate, ecosystems, habitats and biodiversity [1]. The aim of The Green deal is to tackle problems of the climate change by striving to change a block of 27 countries into a fair and prosperous society with a modern, resource-efficient, competitive, low-carbon economy, and protect and strengthen the European Union's (EU) natural capital and improve the quality of life for present and future generations [2]–[4].

Overall goals that were set by the European Union are [3], [4]:
- – To achieve climate neutrality by 2050;
- – To protect human lives, animals, and plants by reducing pollution;
- – To help companies become world leaders in the field of clean products and technologies;

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- To help ensure fair and inclusive adjustment.

The European Union's growth strategy points to the necessity to rapidly change the current situation, invest financial resources in research, promote innovation, ensure clean energy, stimulate industry's transition to a clean economy, act energy-efficiently and resource-efficiently, find solutions for food safety and natural resources management, reduce climate changes and dependence on fossil resources, increase European competitiveness, create new jobs, and encourage the bioeconomy [1], [5], [6].

Today, the bioeconomy is not only considered to be a bio-resource economy, but it also means the sustainable consumption of bio-resources, which creates added value for society. Although it is established in European Union Directive 2008/98/ EK (European Parliament and Council, 2008) that production by-products are not classified as waste, but in establishments they are often considered as one and sent to waste streams or low-value streams, such as, production of biogas or solid fuels [7]. Development of a bioeconomy, based on skills on innovation and investment in knowledge, is inevitably required in turn to achieve a large part of set goals [8].

Bioeconomy is based on three principles of sustainable development – economics, society, and nature. These three pillars – fundamental principles must form a closed cycle, where the by-product of the process (waste product) is the raw material of another process [7].

This kind of approach to bioeconomy raises and enhances the added value of products and replaces fossil fuels in energy production and reduces greenhouse gas emissions.

The aim of the research is to create and offer bioeconomy opportunities, by demonstrating, analysing, and describing possible solution with the help of various examples. This is an illustrative and demonstrative research on how to create possible bioeconomy solutions that would promote the achievement of the goals of the Green Deal and would be suitable for implementation in Latvia.

The study presents a way to select production processes, improve and optimize them, categorize, and classify them according to the principle of sustainability. Analyse the improvement of production processes with different methods and compare them to crystallize the best and most suitable processes from the point of view of bioeconomy and sustainability. A total of 16 different production processes have been selected, based on a significant improvement of an existing production process: process optimization, reduction of residues, full use of added value of emissions or other production process residues, or reduction of electricity consumption and progress towards cleaner production.

In relation to the principles of bioeconomy and the Green Deal, the study provides research into the processes to produce citric acid using the FCM method. Biosynthesis of citric acid is a potential method for creating a new production process using the principles of the best available technology – using waste products processed from apples as the raw material.

Of course, most of the change involves less or more investment, a variety of potential of risk factors and required knowledge, but development is a logical, vital, and inevitable phenomenon in today's world.

2. METHODOLOGY FOR EVALUATION OF BIOPRODUCTS

2.1. Description of the General Method

System dynamics is a computerized approach to comprehend activity and behaviour of complex systems, such as, cities, climate, and ecosystems, for policy analysis and development, which was originally developed by Jay W. Forester. System dynamics is related to how things change over time [9]. It embraces most of what seems important to some people.

System dynamics include the interpretation of real-life systems in computer simulation models. This allows us to see how the system's structure and decision-making policy shape its behaviour. Complex systems are any system with many mutually interacting components (agents, processes, etc.) that are often difficult to understand and solve and that require the development or use of new scientific tools, non-linear models, out-of-balance descriptions, and computer simulations. Complex social systems involve human behaviour and may have concepts that interact in a way that is quantitative (final) and/or qualitative (abstract), and the latter is particularly difficult to include into modelling tools due to their qualitative nature and the consequential challenges. The exclusion of such abstract qualitative concepts may call into question the conclusions that were reached and the relation of the models to reality. In order to be able to explain, predict and understand complexity, it is argued that qualitative phenomenon that can play a significant role in systems must be included. Therefore, analysis of qualitative systems or qualitative modelling is increasingly used to analyse the dynamics of complex systems. Kosko introduced fuzzy cognitive maps (FCM) as a tool for dynamic qualitative system behaviour perception and explanation. FCM is increasingly being used to model and analyse the behaviour of qualitative systems. Over the past 30 years, this fuzzy cognitive mapping (FCM) approach has become increasingly popular due to the simplicity of design and low computing requirements. In order to model the dynamics of the social system, two types of application are mainly used – deductive approach and inductive approach. The deductive approach uses the knowledge acquired by interviewing experts in the field of application, while the inductive approach is an automated and semi-automated approach designed to learn FCM rules based on historical data [10]–[13].

In general, it is considered that FCM has several advantages over traditional quantitative modelling approaches. The advantages of FCM include, for example, the ability to model data in limited environments using natural language, expressing knowledge, perception, experience or beliefs, as formulated by an expert or stakeholder, usually characterized by ambiguous information. Besides, the results of FCM are easy to interpret for the layperson and the public. However, if they're used to model qualitative SD behaviour, traditional FCM also has several drawbacks. These shortcomings are largely due to incomplete:

1. Semantics of causation and thus the limited causation dynamics perception, depiction, and simulation;
2. Inclusion of time relations;
3. Diffusion detection, depiction, and simulation;
4. Dynamics simulation using single-layer perceptron mechanisms.

Several FCM extensions have been developed to overcome these shortcomings, but most of the developed extensions are trying to solve specific problems with traditional FCM and do not try to solve the problems related to modelling FCM dynamics [14]–[16].

FCM consists of concepts (linguistic terms) that are expressed by nodes. Directed arrows with scales explain the relations between concepts. These weights describe the strength of causality with $\{-1.0\}$ and $\{0.1\}$, which, respectively, denotes the decrease and increase of causality. Concepts and their reciprocity are depicted by nodes and directed arrows with their weights explain the layout of a particular system. It is depicted in a matrix that allows to perform standard algebraic operations to find relations between nodes. The FCMs that were introduced by Kosko [10] are simulated using a mathematical formula expressed in the Eq. (1).

$$C_j(t+1) = f\left(\sum_{i=1, i \neq j}^{n} w_{ij} \cdot C_i(t) \right), \tag{1}$$

where

n Number of concepts;

$C_j(t+1)$ Value of the concept in the next iteration;

$C_i(t)$ Value of the concept during the iteration;

w_{ij} Weight of the reciprocity between cause and effect.

Then it is mapped on a predetermined universe in discourse using transformation functions. It is then mapped to a predetermined universe in discourse using transformational functions, the most common are the achievements of the sigmoid and hyperbolic transformation function FCM in relation to modelling and simulation.

Ideally, when modelling a complex qualitative SD, it should have FCM and be able to capture and model causal dynamics, as experts believe. This includes integration and capture of certain causative dynamics properties, which may include, but are not limited to, the following:

- The cause can manifest itself in different conditions or in different ways;
- The cause cannot be two states or an example of strength in time (two states are possible only in quantum superposition);
- The cause is before the consequences, so time dependence is a characteristic;
- The influence of the cause must either increase or decrease;
- The cause in a certain condition can create consequences, which result because of the dynamic time lag, time delay or time reduction;
- The cause can create consequences that are dynamic as a result of changes in position or strength (i.e., they can be nonlinear, non-monotonic, and asymmetric);
- The effect is felt only when there is a change in the state or the strength of the process;
- Influence may be the result of relative causes.

In addition, ordinary FCMs and several achievements of single-layer perceptron are used to model and explain the dynamics of the quality system as a universal event. However, SD, causation can be conditional, probable or possible in terms. Lastly, in the best-case scenario FCM also reflects the uncertainty and indetermination of excerpt knowledge. They can be represented and simulated by using fuzzy systems and FCM, as it was foreseen by Kosko [17]; his approach is suggested and intended as a combination of fuzzy logic and artificial neural networks.

2.2. Description of the Application of the Method for the Evaluation of Bioproducts

The FCM modelling method described will be used in the study to compare different production processes methods. It will help to understand which of them best meets the sustainability criteria set out in the, and to identify potential barriers to obtaining reliable and objective results, while using the FCM method. And whether the use of this type of integrated analysis is appropriate to compare the different production process alternatives that were looked at in the study. FCM modelling requires a sequential set of activities that will ensure that the research objective is achieved in a transparent and understandable way to analyse 16 manufacturing processes.

In order to compare all the production processes described, it is necessary to define the most important criteria. Several criteria are used in this process, making choices more efficient, rational, and clear. The aim of the analysis is to structure the processes to define the

objectives, evaluate the possible alternatives and compare them from different perspectives. The following criteria were selected when evaluating the priority criteria:

1. Environment aspects;
2. Technological aspects;
3. Economic aspects;
4. Social aspects.

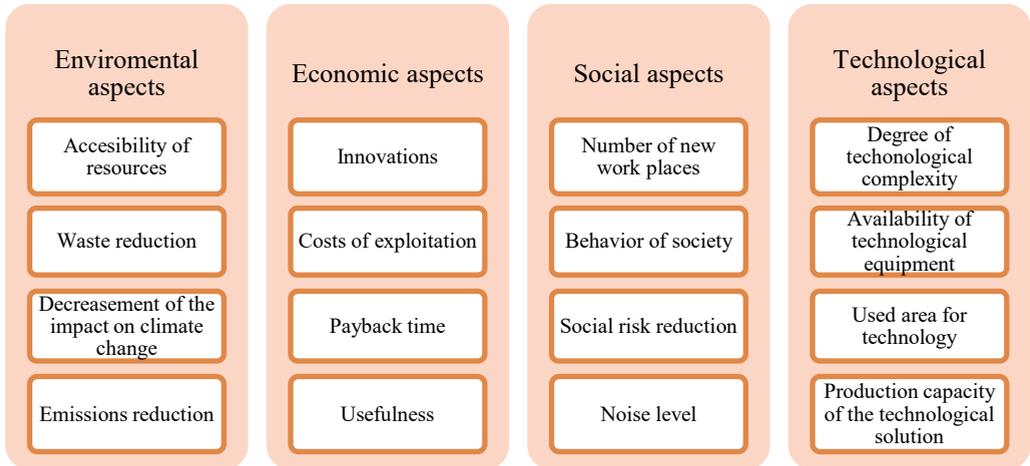| Enviromental aspects	Economic aspects	Social aspects	Technological aspects
Accesibility of resources	Innovations	Number of new work places	Degree of techonological complexity
Waste reduction	Costs of exploitation	Behavior of society	Availability of technological equipment
Decreasement of the impact on climate change	Payback time	Social risk reduction	Used area for technology
Emissions reduction	Usefulness	Noise level	Production capacity of the technological solution

Fig. 1. Aspects of evaluation criteria.

Considering the limitations of the information availability, sustainability, and usefulness indicators from the point of view of bioeconomy have been selected for modelling.

All selected criteria and sub-criteria are qualitative, so they should be assigned numerical values based on the analysis of the production processes performed in the study. The qualitative characteristic approach, unlike the quantitative results approach, makes the results that were obtained in the approbation part of the methodology more subjective. However, if accurate quantitative data on the processes were available, the view on the usefulness performance would be limited.

Each sub-criterion will be assessed with a value from −1 to 1, where the strongest link is donated by 1 and it will denote the best, strongest possible link from the point of view of bioeconomy and usefulness. The rating link one that was obtained in the sub-criterion is comparable to the highest implementation efficiency. Whereas the lowest rating −1 indicates the weakest link or result from the point of view on bioeconomy and usefulness.

3. APPROBATION OF THE METHODOLOGY

Alternatives of the study result are 16 bioproducts. These alternatives are evaluated by the FCM (fuzzy cognitive maps) method, using the *Mental Modeler* tool according to four criteria – environmental, economic, social, and technological aspects. These core criteria are consolidated into 16 sub-criteria and each alternative is assessed on a scale of −1 to 1, with −1 being the weakest link (worst) and 1 being the strongest (best).

3.1. *Reciprocity of Criteria and Sub-Criteria*

Figure 2 sums up the assessments of the environmental, technological, economic, and social aspects that must be analysed. Environmental aspects illustrate the interactions between resource availability, waste reduction, the decreasement of the impact on climate change and emission reduction. For example, the reduction of waste and emissions has a negative effect on the availability of resources because a part of the waste (by-products) and emissions can be used as a raw material for another production process. But a reduction in waste with a strong positive link has a direct positive effect on the environment, as it reduces pollution and therefore less or no waste is generated in production processes. From this point of view, the interactions of all sub-aspects have been looked at, which together result in one of the four aspects. Visually, a blue link that have a positive value from 1 to 0 and brown link whose value is 0 to −1 can be seen. The thicker the colour is the link, the greater is its positive or negative value.
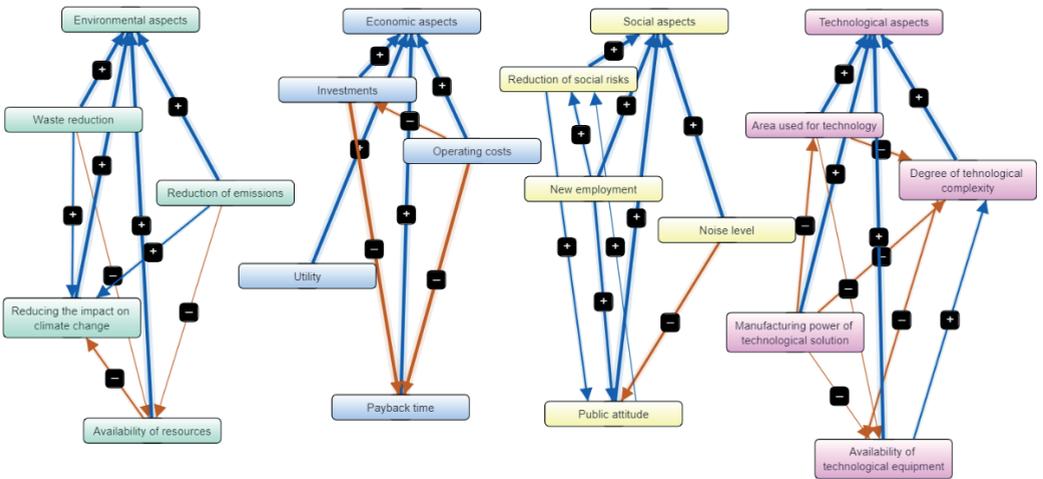

Fig. 2. Links between the interactions of all four aspects and their sub-criteria.

To keep on building the model further, the aspect link described above are used and supplemented with each of the 16 production process name blocks and the same production process usefulness block, which is required for the modelling tool to be able to calculate the total result for a particular production process.

3.2. *Approbation of the Methodology for the Citric Acid Production Process*

All 16 production processes have been analysed and modelled in the study, however, one of the production processes will be shown in detail in this study, but the results for the other 15 production processes will also be evaluated in the results and discussion section, as the structure and approach are analogous to all production process models.
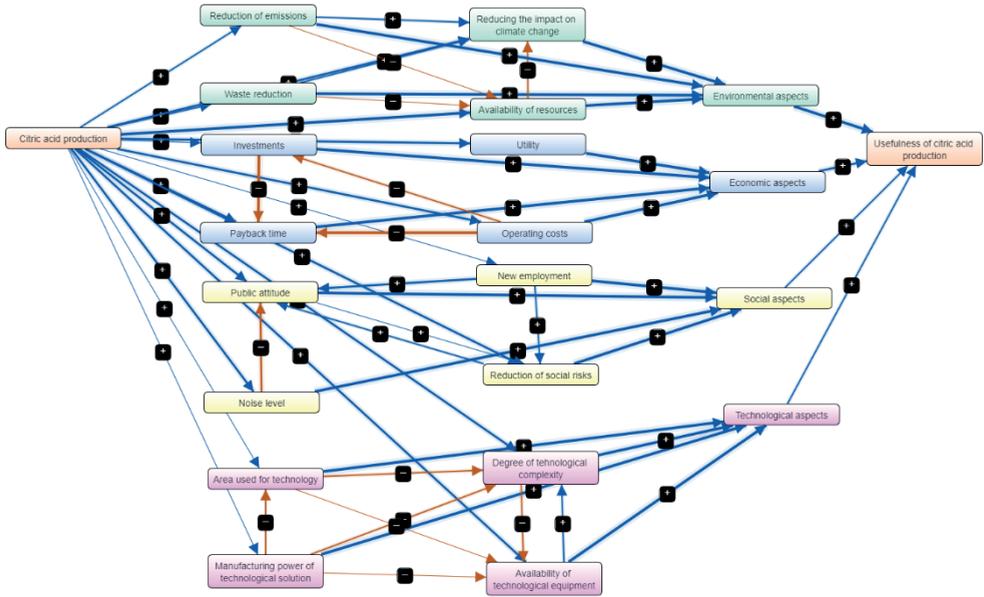
Fig. 3. Advanced visualization model of citric acid production processes.

To make the visualization of the model easier to understand, the group of environmental aspects are coloured green, economic aspects are coloured blue, social aspects – in yellow, and technological aspects are coloured in purple. Whereas the name of the specific variable production process and its usefulness block are coloured orange.

For each production process, links are created for each of the sub-criteria, indicating the strength of the link in the range from −1 to 1, based on expert judgement. For example, Table 1 shows that the payback time for citric acid production is relatively short, so this link has a positive value of 0.7. Meanwhile, the area used for the technology requires about 1 ha, which is estimated at 0.1 positive value.

After completing the visualization part of the model, a quantitative result can be obtained for each of the model positions. The obtained values are shown in Table 1.

TABLE 1. QUANTITATIVE VALUES OF THE CITRIC ACID PRODUCTION PROCESS

Component	Indegree	Outdegree	Centrality
Citric acid	0	6.949	6.949
Environmental aspects	4	1	5
Technological aspects	4	0.48	4,48
Social aspects	4	0.2	4.2
Economic aspects	4	0.81	4.810
Waste reduction	0.47	1.400	1.87
Accessibility of natural resources	1.23	1.19	2.42
Reduction of the impact on climate change	1.21	1	2.21
Emission reduction	0.48	1.339	1.819
Payback time	2.5	1	3.5

Usefulness	0.52	1	3.5
Costs of exploitation	0.5	2.31	2.81
Investments	0.42	2	2.42
Reduction of social risks	1.02	1.25	2.27
Noise level	0.52	1.58	2.1
Public attitude	2.08	1.16	3.24
Number of new jobs	0.09	2,09	2.179
Production capacity of technological solution	0.09	1.680	1.770
Degree of complexity of the technology	1.44	1.28	2.7199
The area used for the technology	0.42	1.28	1.7
Availability of technological equipment	0.960	1.44	2.4
Usefulness of citric acid production	2.49	0	2.49

The table of aspects and sub-criteria of the obtained values is sorted by the central size, it is, the total number of positive and negative links, which shows the most influential aspects and sub-criteria. From the values obtained in the table, it can be concluded that from the point of view of bioeconomy, the most influential aspect of the citric acid production process is the environmental aspect, followed by the economic aspect. In this way, each production process can be reviewed, and the feasible production process can be selected according to any of the proposed aspects. Of course, when working with the model, it is possible to change and view the obtained results by prioritizing social aspect, or any other necessary priority.

Once the quantitative values for each of the sub-criteria have been obtained, the *Mental Modeler* tool has the option to switch to the results section. The main result of the goal is to obtain the efficient results of the production process, which will be in the range from 0 to 1.
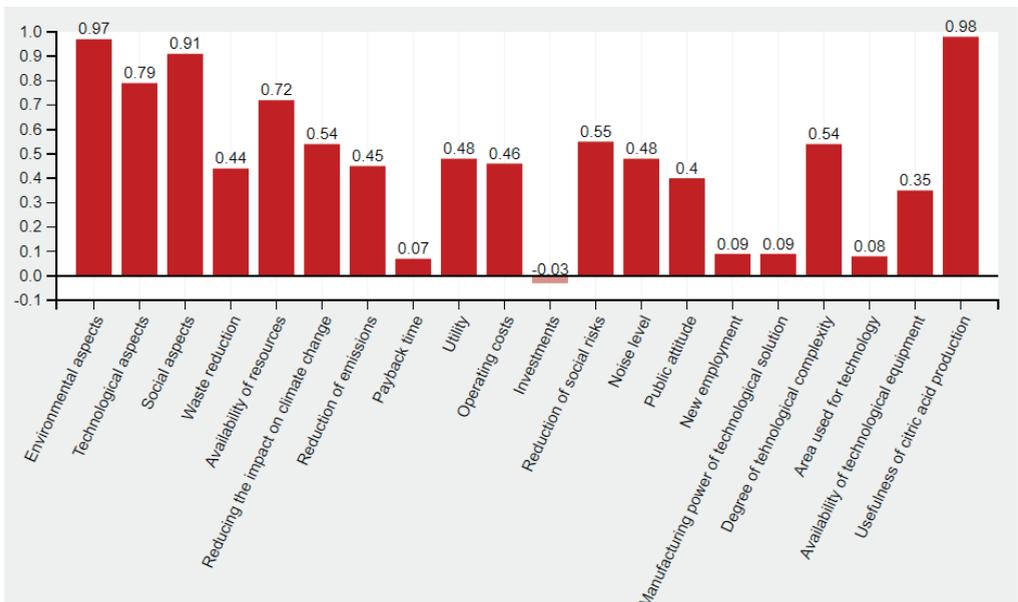

Fig. 4. Results of the citric acid production process.

Fig. 4 shows the main conclusion about the citric acid production process, that is, the citric acid production efficiency is worth 0.97. All production processes described in the work will be compared with this endpoint. As can be seen from the graph, the citric acid production process makes the largest contribution in terms of environmental and social aspects, but the weakest issues in setting up such a plant would be in terms of investment and payback. This is due to the installation of a large amount of necessary industrial equipment and technologies, obtaining relatively small production capacity. Given that the study is prone to sustainability in terms of achieving the objectives of the EU Green Deal, the usefulness of the citric acid production process is very high – 0.97. If the modelling focus was only on the economic aspects, it was thought that the result of this production process would be less positive. Therefore, the author looked for a way to model also changes in priorities.

When designing a model, the *Mental Modeler* tool also provides the ability of influencing and altering priorities at the result and block of scenarios section. Fig. 5 shows the results when the environmental aspects are reduced to −0.49 and the economic aspects are increased to 1. Thus, this simulates the situation where a potential investor wants to assess whether the citric acid production process is economically viable, but the environmental aspects seem less important. In such a situation, the scenario under consideration shows a usefulness value of 0.71, which is also a significant positive value and would be comparable to other alternatives.

Scenario				
Hyperbolic Tangent				
State Prediction: 0%				
Component	+/-	Preferred State	Actual State	
Citric acid production	1			
Environmental aspects	-0.49			
☑ Technological aspects			Increase	
☑ Social aspects			Increase	
Economic aspects	1			
☑ Waste reduction			Increase	
☑ Availability of resources			Increase	
☑ Reducing the impact on climate change			Increase	
☑ Reduction of emissions			Increase	
☑ Payback time			Increase	
☑ Utility			Increase	
☑ Operating costs			Increase	

(a)

692
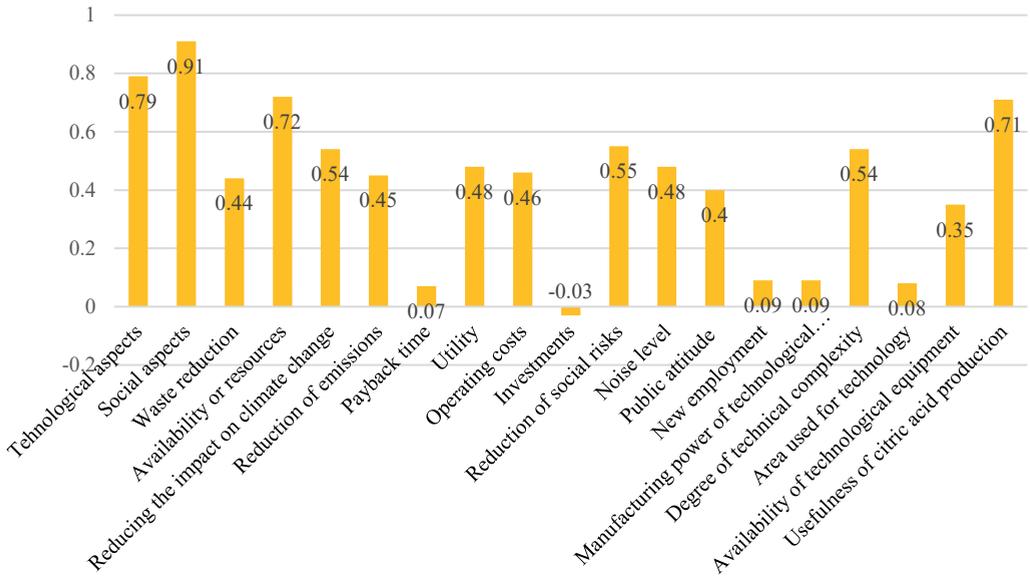
(b)

Fig. 5 (a) and (b). Results of the citric acid production process with increased economic value.

Therefore, such a project is not only environmentally efficient, but also economically viable, and the investor or potential developer can evaluate alternative production processes from different perspectives and compare them with similar criteria.

4. RESULTS AND DISCUSSION

In the previous section an example of a citric acid production process model and the obtained results were described. In the same way, all the 16 production processes were analysed by applying an analogous modelling type and identical criteria. However, as it was mentioned above, the main aim of the study is to obtain data to select from the described production processes the primarily established ones, and to rank them, thus determining, which of the proposed solutions is the most efficient and proves added value from the bioeconomy view towards the Green deal goal achievement. To obtain such an outcome, the result obtained for each production process in the section 'efficiency of the production process' is compared with each other according to the obtained quantitative result on a scale up to 1 (Table 2). Listed results are shown in a bar graph in Fig. 6.

The graph (Fig. 6) shows the obtained quantitative results of 16 production processes in the usefulness comparison. The obtained results show that the most efficient and effective production process is the production of composite materials. This result is justified by the availability of raw materials for composite materials, which are mainly by-products of other production processes: low-quality wood residues and recycled plastics. As well as the demand for such composite materials on the market growing rapidly due to their physical properties, production technologies are relatively simple and available without excessive investment.

Without taking a further look into the positive features of each production process, which have brought the described production process closer to the high result obtained, we conclude that eleven of the described sixteen production processes have reached very high values in

the range of 0.9 to 1 and all eleven production processes correspond to high bioeconomy efficiency towards the goals of the Green deal, consequently these production processes are very valuable and should be primarily implemented in the economy by investing in production facilities.

TABLE 2. USEFULNESS OF PRODUCTION PROCESS

|	
Citric acid production	0.97
Synthesis of silver nanoparticles	0.96
Manufacture of composite materials	0.98
Nanocellulose production	0.92
Manufacture of toiletry from whey	0.97
Xylan production	0.92
Polykactide production	0.97
Manufacture of natural nettle fibres	0.29
Biodiesel production	0.73
Production of Dendrolight cellular material	0.98
Pellet production	0.83
Bioethylene production	0.68
Cellulose production	0.94
Tannin-based foam production	0.9
Coniferous extract production	0.96
Lignin production	0.83
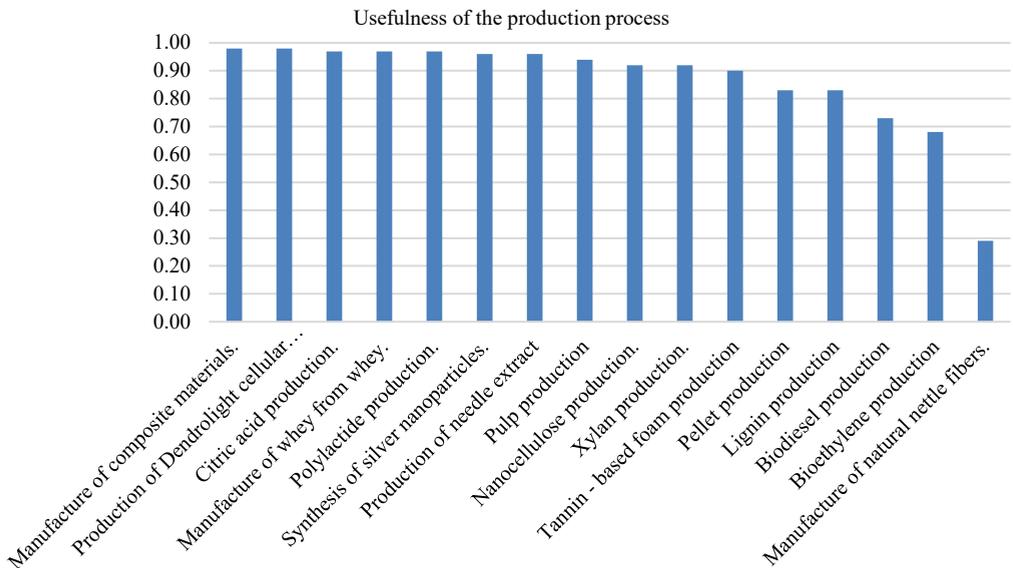
Fig. 6. Summary of efficiency of production processes.

Conversely, the production processes of biodiesel and bioethylene, although very valuable for replacing fossil fuels and increasing the independence of non-oil-producing countries from fossil resources, are still very technologically complex and require huge investments in their production and are currently reducing their production economic viability. However, the rapid development of science and technology will inevitably bring the production of biodiesel and bioethylene closer in the next decade.

The weakest result (0.29 out of 1) was obtained in the production of natural nettle fibres. This result is due to the competition of this production process for agricultural land with the food industry and the low competitiveness of the resulting product in the textile industry, as it would be very difficult to justify the production of nettles in large areas and processing them into textile products from the environmental aspect and economics aspect point of view.

Considering the objectives of the study, the obtained results are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate to compare the various alternative production processes considered in the work.

ACKNOWLEDGEMENT

REFERENCES

[1] Heimann T. Bioeconomy and SDGs: Does the Bioeconomy Support the Achievement of the SDGs? *Earth's Future* 2019:7:43–57. https://doi.org/10.1029/2018EF001014

[2] Muizniece I., Kubule A., Blumberga D. Towards understanding the transdisciplinary approach of the bioeconomy nexus. *Energy Procedia* 2018:147:175–180. https://doi.org/10.1016/j.egypro.2018.07.052

[3] European Commission. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, COM (2011) 112 final. Brussels: EC, 2011.

[4] UNEP. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. UNEP, 2011

[5] Bloomfield J., Steward F. The Politics of the Green New Deal. *The Political Quarterly* 2020:91(4):770–779. https://doi.org/10.1111/1467-923X.12917

[6] Linnér B. O., Wibeck V. Conceptualising variations in societal transformations towards sustainability. *Environmental Science and Policy* 2020:106:221–227. https://doi.org/10.1016/j.envsci.2020.01.007

[7] Vamza I., *et al.* Bioresource utilization index – A way to quantify and compare resource efficiency in production. *Journal of Cleaner Production* 2021:320:128791. https://doi.org/10.1016/j.jclepro.2021.128791

[8] Ruse A., Pubule J. The Boundaries of Scientific Innovation in the EU Green Deal Context. *Environmental and Climate Technologies* 2022:26(1):115–128. https://doi.org/10.2478/rtuect-2022-0010

[9] Blumberga A., *et al.* Modelling the Baltic power system till 2050. *Energy Conversion and Management* 2016:107:67–75. https://doi.org/10.1016/j.enconman.2015.09.005

[10] Gray S., *et al.* Mental modeler: A fuzzy-logic cognitive mapping modeling tool for adaptive environmental management. *Proceedings of the 46th International Conference on Complex Systems* 2013:963–973. https://doi.org/10.1109/HICSS.2013.399

[11] Gray S., Zanre E., Gray S. Fuzzy Cognitive Maps as representations of mental models and group beliefs: theoretical and technical issues. Fuzzy Cognitive maps for Applied Sciences and Engineering - From fundamentals to extensions and learning algorithms. Springer Publishing, 2013.

[12] Gray S., *et al.* Modeling the integration of stakeholder knowledge in social-ecological system decision-making: Benefits and limitations to knowledge diversity. *Ecological Modelling* 2012:229:88–96. https://doi.org/10.1016/j.ecolmodel.2011.09.011

[13] Gray S., *et al.* Are local coastal managers detecting the problem? Assessing stakeholder perception of climate vulnerability using Fuzzy Cognitive Mapping. *Ocean and Coastal Management* 2014:94:74–89. https://doi.org/10.1016/j.ocecoaman.2013.11.008

[14] Henly-Shepard S., Gray S., Cox L. The use of participatory modeling to promote social learning and facilitate community disaster planning. *Environmental Science & Policy* 2015:45:109–122. https://doi.org/10.1016/j.envsci.2014.10.004

[15] Nayaki A., *et al.* Local-scale dynamics and local drivers of bushmeat trade. *Conservation Biology* 2014:28(5):1403–1414. https://doi.org/10.1111/cobi.12316

[16] Halbrendt J., *et al.* Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. *Global Environmental Change* 2014:28:50–62. https://doi.org/10.1016/j.gloenvcha.2014.05.001

[17] Kosko B. Fuzzy cognitive maps. *International Journal of Man-Machine Studies* 1986:24(1):65–75. https://doi.org/10.1016/S0020-7373(86)80040-2

Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development

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Abstract** – **The Waste Framework Directive mandates that, starting from January 1, 2025, separate collection of textiles must be introduced in all Member States of the European Union. The aim of separate collection is to promote the circular economy in the textile system by creating favorable conditions for recycling and reuse. However, in order to promote recycling, there are still challenges in terms of textile variety and mixtures. Currently, there are no commercially viable technologies to recycle mixed textiles without sorting back into textiles or high value-added products. Therefore, the aim of this study was to determine if there are products in the research process that could be obtained from post-consumer mixed textile waste and, if so, to assess which is the most suitable for further development based on economic, environmental, social and technical factors. Two methods were applied: literature analysis and multi-criteria decision analysis. A total of 27 research articles were identified, but only four were selected for further analysis based on their relevance to the research objective. The products obtained in the selected studies were (1) bio-oil and terephthalic acid, (2) textile-reinforced composite for building applications, (3) mycelium-based composite for thermal insulation and (4) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate. The multi-criteria decision analysis showed that mycelium-based composite has the highest potential for further development. Future research should focus on scaling up the production of mycelium-based material and conducting a more detailed assessment of the economic, social and environmental impacts.

Keywords** – **Circular economy; multi-criteria decision analysis (MCDA); mycelium-based material; sustainable development goals (SDGs); value-added products.

1. INTRODUCTION

Production and consumption of textiles is increasing worldwide, and so is the amount of textile waste [1]. Globally, around 75 % of clothing waste is landfilled or incinerated, 25 % is recycled or reused and only 1 % is recycled back into textiles [2]. The transition to a circular economy in the textile sector is in line with several United Nations Sustainable Development Goals [3]. In particular, it would contribute to the achievement of Goal 12 – Responsible Consumption and Production.

Textile waste is also a pressing issue in the European Union (EU), with the fourth highest impact on primary raw material and water consumption and the fifth highest impact on greenhouse gas emissions [4]. For this reason, the EU has identified textiles as one of the

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seven key product value chains to be targeted in the transition to a circular economy. As part of this transition, The Waste Framework Directive mandates that, starting from January 1, 2025, separate collection of textiles must be introduced in all EU Member States [5]. However, separate collection of textiles is only the first step, as sorting and recycling are not yet sufficiently developed in the EU [6], [7]. If sorting and recycling capacity is not increased alongside separate collection, there is a risk that sorted textiles will end up in incinerators or landfills or be exported as waste outside the EU [7].

Textile waste can be divided into three streams: post-industrial waste, pre-consumer waste and post-consumer waste [1]. Post-industrial waste is all textile waste generated during the production process. Pre-consumer waste already exists as products, but is either damaged or has not been sold or used. The last and largest stream is post-consumer waste, which is waste generated after use. EU textile waste amounts to 15 kg per capita, 85 % of which is made up of consumer discarded clothes and home textiles – post-consumer waste [6]. In this study, this waste stream is defined as mixed post-consumer textile waste. This waste is a mixture of different types of textiles, mainly cotton and polyester, with added components such as buttons and zippers and added substances such as dyes, coatings and flame retardants [8], [9]. All of these aspects create barriers to current textile recycling technologies.

Part of the solution could be to improve sorting so that textile flows are as clean as possible, each with its own recycling options. However, there are a number of obstacles to achieving this. Firstly, sorting is currently largely done manually, which makes the process more costly and time consuming [9]. Furthermore, textiles are not just mono-materials that are suitable for recycling. Instead, textile waste is usually a multi-element waste, and often blended. Therefore, textile waste can be divided into more than 300 different categories depending on size, composition and type of fibers [1]. Some of them are difficult to recycle or need specialized technologies. In addition, the quality of textile waste is not guaranteed as textiles may be contaminated or defective [1]. These sorting barriers raise the question whether there is a solution to recycle mixed textile waste as a single stream without much sorting.

Large number of studies have been carried out on the recycling of different textiles [10]–[13], including blended textiles [14], [15]. However, to the best of the author's knowledge, no study has yet summarized research on post-consumer mixed textile waste recycling. Also, there are currently no commercially viable technologies to recycle mixed textiles back into textiles or high value-added products [8], [16]. Therefore, the aim of this study was to determine if there are products in the research process with Technology Reediness Level of 3–5 that could be obtained from post-consumer mixed textile waste and, if so, to assess which is the most suitable for further development based on economic, environmental, social and technical factors. Literature analysis was used to identify products, and multi-criteria decision analysis was used to evaluate and compare them. Multi-criteria decision analysis was chosen because it is suitable for comparing products on the basis of selected criteria [17], [18].

2. METHODOLOGY

Multi-criteria decision analysis (MCDA) is a well-established method for making decisions. It is applicable in any field where it is possible to define a problem, criteria and alternatives to be compared with each other [19]. There are several MCDA methods, but each method has its own calculation steps, so the results may differ even though the input data are the same.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was chosen for this research, based on the author's previous study comparing products [18], which is also the objective of the present analysis. The TOPSIS method has the benefits of relatively simple calculation steps, an unlimited number of criteria and alternatives, and the input data

can be both qualitative and quantitative [19]. The resulting score is the distance of the alternatives to the ideal point, which in this method is equal to one, meaning that the closer the score of an alternative is to one, the better the alternative. MS Excel was used for the TOPSIS calculations.

The MCDA analysis followed the steps developed in the author's previous study [18]:

1. Product identification. The first step is a literature analysis to identify products.
2. Criteria selection and data collection. This stage involves selecting criteria and collecting input data.
3. TOPSIS analysis. In this step, calculations of the analysis are carried out and the final results are obtained.
4. Sensitivity analysis. The final step is to validate the results using a sensitivity analysis.

2.1. Product Identification

The aim of the literature analysis was to identify products that can be obtained from post-consumer mixed textiles. The scope of this study was limited to the scientific literature to ensure that the focus is on peer-reviewed information. Three scientific databases, Scopus, Science Direct and Web of Science, were used. The keywords "post-consumer mixed textile recycling" were used in all databases. Only in Web of Science an insufficient number of articles was found (33 results), so the keywords were changed to "textile waste recycling products". In total, a relatively large number of publications were found for these keywords: Science direct (2678 results), Scopus (944), Web of Science (799). Content in English and less than 10 years old (from 2014) was selected. The first 100 items in all databases were reviewed sorted by relevance. This was done since, approaching 70 items, they started to be outside the study's scope, therefore it was decided to stop the review at 100 items. For further research, items were filtered based on title and abstract. This was an initial screening to find articles on textile recycling. The selected studies were then fully read to select studies according to two criteria: recycled textiles are post-consumer and mixed textiles. The aim was to find recycling process that met both criteria.

2.2. Criteria Selection and Data Collection

All the calculations are based on the input data, the selected alternatives and the criteria. For further analysis, products and product sets produced from post-consumer mixed textile waste were selected to be alternatives. The products were categorized on the basis of research articles. For example, the Andini *et al.* study [16] produced four main products, but these are not considered separately as they are all produced in the same production cycle and using the same raw material.

After determining alternatives to compare, the next step was to select the criteria. The criteria were selected on the basis of their relevance to the study objective and the available data. To assess the potential for product development, the criteria cover four categories: environmental, economic, social and technical aspects. These categories were chosen because technical parameters are important to assess the technology, while sustainability aspects are important to assess its development [20]. The nine criteria selected are shown in Table 1. For all criteria, the ideal value is the maximum value, which means the higher the value the better.

TABLE 1. CRITERIA FOR MULTI-CRITERIA DECISION ANALYSIS

Criteria category	Criteria	Description
Environmental aspects	Environmental impact	Comparison of global warming potential (GWP) from life cycle assessment of a new and a conventional product (reduction in GWP)
	Resource efficiency	Usage of other waste materials in production (weight proportion, %)
	Longevity and recyclability	Product lifetime and end-of-life potential (score)
Economic aspects	Product price	Comparison of price for the new and conventional product (reduction in price)
	Market demand	Global market size assessment (billion EUR)
Technical aspects	Technology maturity	Level of technological readiness (TRL 1-9)
	Level of research	Studies carried out on similar products (score)
	Market competitiveness	Comparison of properties for the new and conventional product (score)
Social aspects	Social aspects	Evaluation of human health and safety risks during production (score)

2.2.1. Environmental aspects

Life cycle assessment is a method for quantifying the environmental impacts of products and processes. In order to gain insight into potential environmental impacts, LCA studies were used to assess this criterion, as it has been done previously in similar MCDA studies [17], [21]. The products are innovative, so no LCA studies have yet been carried out for the specific cases. Therefore, similar products with LCA studies were selected. The GWP was used as a quantitative indicator, which is commonly used in environmental impact communication [22]. The conventional product was selected based on the intended use of the new product, what it can be compared to in terms of performance and what is commonly used now. If the study already had data on conventional products, these were used for comparison. But if not, they were obtained from the *Ecoinvent* 3.10. database using the same method as used in the comparison study. The value of the existing product was divided by the value of the new product to get estimate of the number of times the environmental impact can be reduced. If the value is less than one, this means that the environmental impact of the new product likely is higher based on the GWP. This approach was chosen to assess not only the potential environmental impacts of the alternatives, but also to compare the alternatives with the products currently in use. The life cycle impact assessment method and the scope of the system were taken into account in the comparison.

To assess the potential of the circular economy, the criterion "Resource efficiency" was included. The products studied already contribute to the circular economy because the raw material used is textile waste. Therefore, this criterion assesses whether additional by-products or waste are used during production that would increase the contribution to the circularity and avoid the use of virgin materials. It is determined by weight in proportion to the final product. If no other residues are used, the alternative receives a score of zero.

The first two criteria relate more to the production phase. The criterion "Longevity and recyclability" was introduced to also assess the use phase and end of life. It includes an assessment of the lifetime and recyclability of the product. Both aspects were evaluated on a three-point scale. Scoring system for recycling: (1) not recyclable or generally not recycled, (2) recycled or biodegradable, (3) closed-loop recycled. This rating was chosen as the circular

economy prioritizes resource circularity in closed system and other uses of bio-based materials before nutrients are returned to natural system [2]. Lifetime aspect points system: (1) single use, (2) used up to 10 years, (3) longer than 10 years. The points were multiplied with each other, giving a maximum of 9 points.

2.2.2. Economic aspects

The price of a product is an important indicator of whether it will be economically viable and competitive. Price is a specific indicator (price per unit of product) rather than other economic indicators which are more difficult to compare, for example initial investment is more dependent on production volume. As with the environmental impact criterion, innovative products are unlikely to be subject to an economic assessment and will therefore be compared with similar products. The conventional product price was also identified for comparison. The value of the existing product was divided by the value of the new product to get how many times cheaper the new product would be. If the value is less than one, it means that the price of the new product is higher and it is not economically justified at this time. The other economic aspect focuses on the demand side. Global market size was used to determine whether a product is in demand. The higher the market estimate, the more the product is in demand. The market size estimates were based on publicly available data.

2.2.3. Technical aspects

The Technology Readiness Level (TRL) was assessed to determine how mature and ready for scaling up the technologies developed in the study are. The TRL has proven to be a very effective way of communicating the progress of new technologies in different fields [23]. It is assessed on a 9-point scale. In order to better understand and evaluate the products, more extensive descriptions of the TRL from J. Mankins publication [23] were used.

To assess how well a product is being researched, the criterion "Level of research" was introduced. This measured the number of publications on a given topic. In order to effectively assess this criterion, only one database was chosen, and that was Scopus. The key words for each alternative were based on the type of product, the method used and included the term "textile". The publications found were assessed qualitatively by looking at the abstract and the title. Only publications containing the same or similar product and using textiles were selected.

The criterion "Market competitiveness" was added to assess the technical performance of the product. This criterion looked at the properties of the selected alternatives as determined by their studies and then compared them with those of the conventional product. Each product had its own characteristics, as each has its own application. If the comparison was already made in the study, it was used, if not, the characteristics of the conventional product were additionally selected. The product's characteristics compared to similar products were evaluated with points. The scoring system for the criterion was as follows: (1) characteristics are lower than those of products on the market, (2) characteristics are more or less the same, (3) improved characteristics.

2.2.4. Social aspects

Social factors can be quantified using social LCA or indicators such as human health [17] and job creation opportunities [24]. To the best of the authors' knowledge, no social LCA has been carried out for the alternative or similar products under consideration. Quantitative data on social factors for the alternatives were available for more generic sectors such as government, education and manufacturing. That was not applicable in this case as all

alternatives fall within the same sector. It was therefore decided to assess the risk to human health in the product manufacturing process using a scoring system based on the information available in the literature. The following evaluation system was used: (1) high risk work, (2) medium risk and (3) minimal risk work.

2.3. TOPSIS Analysis

To start the calculation, the criteria must be given a weight indicating the importance of the criterion. The weight can be determined by different methods, such as the analytical hierarchy [19] process or sensitivity analysis [18]. In our case, there are more than seven criteria, which means that the analytical hierarchy process cannot be used as the results would be inconsistent [19]. In this study, it was decided that all criteria will have equal importance which means that all criteria will be given equal weight.

After determining the input data and criteria weights, the TOPSIS method was used in the following calculations. TOPSIS method has five steps [19]:
1. Normalization of decision matrix:

$$R = \frac{X}{\sqrt{\sum X^2}}, \tag{1}$$

where R is normalized matrix value and X is criteria value.
2. Calculation of the weighted decision matrix:

$$V = R \cdot W, \tag{2}$$

where V is weighted value and where W is weight of criteria.
3. Defining ideal and anti-ideal values: V^+ is maximum value of the weighed values un V^- is the minimum value.
4. Calculation of the ideal and anti-ideal values:

$$d_a^+ = \sqrt{\sum \left(V^+ - V\right)^2}, \tag{3}$$

where d_a^+ is distance to the ideal solution.

$$d_a^- = \sqrt{\sum \left(V^- - V\right)^2}, \tag{4}$$

where d_a^- is distance to the anti-ideal solution.
5. Calculation of relative proximity:

$$C_a = \frac{d_a^-}{d_a^+ - d_a^-}, \tag{5}$$

where C_a is relative proximity to the ideal solution. In the end, the best alternative can be determined by comparing the relative proximity to the ideal solution.

2.4. Sensitivity Analysis

Sensitivity analysis is carried out to examine the impact of criteria on the results and to validate the results. Sensitivity analysis steps [25]:

– In this method, the weights are initially considered to be the same:

$$w' = \frac{1}{n} , \qquad (6)$$

where w' is initial weight and n is number of criteria.

– Then the weight for one criterion is changed, depending on the unitary variation ratio:

$$w'_k = \beta_{km} \cdot w' , \qquad (7)$$

where

w'_k weight, that is subject to change;

β_{km} unitary variation ratio;

$k = 1, 2, 3 \ldots n, m = 1, 2, 3 \ldots n$.

– To obtain the weight of the other criteria Eq. (8) is used:

$$w'_{km} = \frac{(1 - w'_k)}{(n-1)} , \qquad (8)$$

A sensitivity analysis with five unitary variation ratios was carried out ($\beta_k = 0.01; 0.5; 1.5; 2; 2.5$). Larger ratios such as 3 and 4 were also tested, but the criteria are sufficiently sensitive to change so the original ratios were kept. The ratios were increased by 0.5 steps. This means that with each further ratio, the impact (weight) of the criterion increases proportionally. The resulting weights are then applied in TOPSIS calculations to get the results of the Sensitivity analysis. This was done for all criteria.

3. RESULTS

3.1. Identified Textile Recycling Products

Product identification resulted in 27 articles on the recycling of textiles into products. Further analysis of the articles was carried out to group the products based on two criteria concerning input textile waste: textile fiber type (polyester, cotton, mixed, etc.) and waste type (industrial or post-consumer). A list of products resulting from these articles is given in Table 2. In eight articles, the textile waste came from industry, which is not relevant for our further analysis as these textiles have not been used by a consumer. Most of the articles focused on a certain type of textile or groups of textiles, in some cases even very specific textiles like silk, denim, lyocell and leather. As shown in Table 2, the analysis resulted in only four articles covering the recycling of mixed post-consumer textiles, which was the objective of the analysis. The products obtained in the selected studies were (1) bio-oil and terephthalic acid [8], (2) textile-reinforced composite for building applications [26], (3) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate [16] and (4) mycelium-based composite for thermal insulation [27].

TABLE 2. SUMMARY OF PRODUCTS WHICH CAN BE OBTAINED FROM TEXTILE RECYCLING

Textile type / Waste type	Industrial	Post-consumer
Polyester	Polyurethane foams [28]	Terephthalic acid (TPA) [29], monomers like bis(2-hydroxyethyl) terephthalate (BHET) and bis(2-hydroxyethyl) terephthalamide [30], TPA and ethylene glycol [31]
Cotton	Thermal insulation [32]	Composites for industrial applications [33], glucose solution [34], [35], fashion accessories [36], vermicompost for fertilizer [37]
Nylon	–	Fine fibrous membrane [38]
Denim	Sound absorbing material [39]	Fire retarding composite board [40]
Silk	–	Luminescent carbon dots [41]
Lyocell	Adsorbent for heavy metals [42]	–
Leather	Leather-like yarns [43]	–
Cotton/polyester	–	Cellulose fibers [44], cellulose and PET films [45], 3D printing filament [46], fungal cellulase and polyester [47]
Viscose/polyester and viscose/polyamide	–	Synthetic fibers and lactic acid [48]
Acrylic and wool	Thermal insulation [49]	–
Cotton, cotton/polyester and acrylic	Biochar as fabric additives [50]	–
Mixed textile	–	Bio-oil and TPA [8], textile reinforced composites for building applications [26], BHET crystals, spandex monomers, cotton and nylon [16], mycelium-based composite for thermal insulation [27]

3.2. Input Data for Alternatives

Next products from four studies were investigated to later be compared in the TOPSIS analysis – (1) bio-oil and terephthalic acid [8], (2) textile-reinforced composite for building applications [26], (3) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate [16] and (4) mycelium-based composite for thermal insulation [27]. Only these studies were selected as they deal with mixed post-consumer textile recycling.

Matayeva *et al.* published a study in 2022 on the recycling of mixed textiles using hydrothermal liquefaction [8]. The study did not use actual mixed textile waste, but rather combined textile waste with a known composition based on the proportions of fibers produced globally. The processing was carried out on a laboratory scale using hydrothermal liquefaction without any pre-treatment steps such as sorting, dye removal, etc. The results showed that this method could yield 3–9 wt.% bio-oil and 38–54 wt.% TPA. TPA can further be used in the production of plastics, packaging, textiles, resins, composites, paints, etc. [51]. The composition of the bio-oil considered in the study makes it difficult to upgrade to a drop-in fuel. Instead, it could be upgraded and used as a chemical feedstock [8].

The second alternative is a textile fiber reinforced composite (TRC) for use in construction [26]. The prototype panels were produced on a laboratory scale by mechanically extruding mixed textile waste using isothermal hot pressing in a steel die. In addition, residual wood

sawdust from the furniture industry was added as a secondary filler. To improve processing and the final product, maleic anhydride grafted polypropylene and polypropylene textile fleece were added as the thermoplastic matrix phase. The resulting material properties in terms of moisture resistance, load-bearing and non-load bearing applications are optimal compared to wood particleboards. Overall, they could be used in load-bearing structures as flooring, walling and division systems, as well as for interior linings such as ceilings or acoustic absorbers [26].

The third study looks at how closed-loop recycling could be promoted by extracting BHET crystals, spandex monomers, cotton and nylon from mixed textiles [16]. The method used was chemical conversion of post-consumer mixed textile waste using microwave-assisted glycolysis over a ZnO catalyst followed by solvent dissolution. As a result, the polyester from the mixed textile waste is completely converted into BHET crystals with 93 % purity. The most valuable of the spandex monomers obtained was 4.4′-methylenedianiline. However, further optimization is needed to increase its selectivity from other diphenyl-containing molecules. Formic acid and dyes have remained on the resulting cotton, making further processing more difficult. The obtained nylon has a reduced average molecular weight, which limits its use in applications requiring high tensile strength, stiffness and melting point. Overall, further development of this method has a potential to result in a global textile circularity rate of 88 % [16].

The final alternative considered was a mycelium-based composite for thermal insulation. In the reviewed study [27], a biocomposite was developed by cultivating *Pleurotus pulmonarius* fungus in agro-industrial waste (grass cuttings, dry leaves and sugarcane bagasse) and post-consumer mixed textile waste. The input material was recycled ground textiles that had already been processed by the supplier. The study succeeded in using textile materials to cultivate fungi, thus producing a sustainable and cost-effective construction material.

Before the TOPSIS calculations can be made, input data must be collected for each product. Table 3 summarizes all input data and the following subsections describe the data sources and assumptions made.

TABLE 3. INPUT DATA FOR MCDA

Criteria	Alternatives			
	Bio-oil and TPA	Textile-reinforced composite	BHET crystals, spandex monomers, cotton, nylon	Mycelium-based composite
Environmental impact, times	0.99	2.63	6.83	4.59
Resource efficiency, %	0	30	0	70
Longevity and recyclability, score	3.5	3	6	3
Product price, times	1.07	0.05	1.65	18.33
Market demand, billion EUR*	39	6	24	57
Technology maturity, score	3	5	3	3
Level of research, score	1	25	0	6
Market competitiveness, score	1	2	1	1
Social aspects, score	2	2	3	1

* The exchange rate used was 1 USD = 0.88 EUR (23.04.2025)

3.2.1. *Environmental impact*

The LCA studies were examined for environmental impact. For the first alternative, two products are considered at the same time, so the average value between these products is taken into account in each criteria assessment. Bio-oil was compared to a study where bio-oil was obtained from agricultural waste by hydrothermal treatment [52]. The gate-to-gate GWP of this product was 2.05 $kgCO_2eq/kg$. Carbon credits have been included in this assessment. The LCA method used was ReCiPe. In selected study, the new product was not compared to the conventional product, so the GWP was derived from the *Ecoinvent* database using the same LCA method. Crude oil was chosen for comparison because the bio-oil produced in the study is not a drop-in fuel and still needs further processing [8], [52]. As the study does not specify the region of the LCA model [52], a market activity was chosen that covers several countries but is cradle-to-gate. The transformation dataset, which is gate-to-gate, was country specific. The GWP for crude oil in the global region market is 0.65 $kgCO_2eq/kg$ [53].

There are no studies in which TPA has been produced by hydrothermal liquefaction. Therefore, it was compared with the closest product that could be found, a biobased TPA produced using miscanthus as a feedstock in a thermochemical processing (fast pyrolysis). These products have different raw materials and processes, but both focus on the sustainable production of TPA. The cradle-to-gate GWP of this product was 1.04 $kgCO_2eq/kg$ [54]. In the same study it is compared to conventional TPA and its impact was estimated to be 1.72 $kgCO_2eq/kg$.

The TRC was compared with an LCA study looking at composites made from natural fibers and recycled textiles [55]. The uncertainty arises from the fact that the study does not specifically mention what the materials could be used for. However, it was the closest product in terms of input materials and manufacturing process for which an environmental impact assessment was available. The reference material was a composite made of flax and recycled polyester fabric. Its cradle-to-gate GWP was 3.0 $kgCO_2eq/kg$. The study did not compare these materials with conventional products, so the GWP of glass fiber reinforced plastic was obtained [56]. The method used was the ReCiPe Midpoint (E) method from the study reviewed. The GWP obtained was 7.9 $kgCO_2eq/kg$.

The study on the third alternative [30] refers to a previously conducted LCA study on this recycling process. It was therefore used as a reference study. It dealt with the microwave-assisted recycling of PET bottles into BHET crystals [57]. The resulting cradle-to-gate GWP was 0.64 $kgCO_2eq/kg$. This was compared to conventional BHET oil-based production with a GWP of 4.37 $kgCO_2eq/kg$. For this alternative, only one product was considered as it is produced using the same processing method. However, the further treatment used in our alternative to separate the spandex monomers, nylon and cotton is not taken into account.

The mycelium-based material was compared with an LCA study of a mycelium isolation material using sawdust as a substrate [58]. The resulting cradle-to-gate GWP was 0.64 $kgCO_2eq/kg$. Most of the impact (95 %) was due to electricity, so the raw materials do not play a significant role. The study looks at the German situation and mentions that Germany has a high share of fossil fuels in the electricity mix. Therefore, the impact globally or in other countries could be even lower. It was compared with extruded polystyrene insulation, which has a GWP of 2.94 kg [58].

3.2.2. *Resource efficiency*

In only two cases – TRC and mycelium-based composites – were additional residual materials found to have been used. In the case of TRC, wood fibers from the furniture industry were used as a second filler. It accounted for 30 % of the weight of the material [26].

Mycelium-based material requires a lignocellulosic substrate on which the fungi can feed. A wide variety of plant substrates can be used as feedstock like jute, flax and straw [59]. In the study by Gomez *et al*. agro-industrial waste such as grass cuttings, dry leaves and sugarcane bagasse were used [27]. These accounted for 70 % of the substrate mass.

3.2.3. Longevity and recyclability

Bio-oil can be used as a fuel and in the production of food flavorings, aromatics, olefins, resins, adhesives, agrochemicals and fertilizers [60]. Most of these goods can be considered as single-use and nonrecyclable. TPA is used in plastics, packaging, textiles, resins, composites and paints [51]. As it can be used in the production of textiles, it was considered in this analysis to be recyclable in a closed loop. Textiles have an average lifespan of up to six years [61].

Recycling of fiber-reinforced composites is challenging due to their hardness and chemical stability [62], [63], so for this analysis it was assumed that TRC is generally not recycled. As the TRC in the present case is intended for construction, its lifetime is longer than 10 years, as the lifetime of a building is considered from 20 to over 100 years [64].

The textile fibers (nylon and cotton), spandex monomers and BHET crystals obtained in the Andini *et al*. study can be recycled back into textiles [16]. Therefore, the analysis assumes that a closed loop recycling can be established. As the recycling assumption is based on textiles, a lifetime of up to 10 years is assumed, as mentioned above.

Mycelium-based materials are considered biodegradable [65]. However, in our mycelium-based material, part of the substrate is a mixed textile containing synthetic materials. Therefore, such a material would most likely not be biodegradable as synthetic textiles are not biodegradable [66].

3.2.4. Product price

The price of TPA was taken from a socio-economic analysis of the enzymatic recycling of PET to produce TPA [67]. The study obtained a minimum selling price of 1.93 USD/kg. This was compared to the market price of virgin TPA in 2021, which was around 1 USD/kg [67]. For bio-oil, the example was taken from a study in which bio-oil was extracted from food waste by hydrothermal oxidation [68]. A minimum selling price of 104 USD/ton was obtained. The market price of bio-oil was set at 168 USD/ton [68].

There were no studies on the possible prices of TRC, so the prices of fiber-reinforced composites were investigated. A study was found which summarized the prices of hybrid natural fiber and synthetic fiber composites for many applications. The study summarized the prices of 144 products (see Table 6 in the study) [69]. The average price of 12.15 USD/kg was taken. As for the environmental impact criterion, the aim was to compare the product with a glass fiber reinforced composite. Economic performance for this material could not be found in the scientific literature, so online shops were taken into account. The price of the glass fiber reinforced composite was found to be between 0.61 and 0.71 USD/kg [70]. The average price was used in the TOPSIS calculations.

For the third alternative, it was decided not to look for a comparable price, as the process results in several products and is highly innovative. Also, the study itself carried out a socio-economic assessment, which more accurately reflects the economic performance [16]. Therefore, this alternative was an exception and it was not prices that were compared but investments. A textile feed throughput of 500 kg/h was assumed for the socio-economic assessment of mixed textile recycling [16]. For a 10-year economic life cycle of the project, an interest rate of 20 % was taken into account. This resulted in total operating costs of USD

92.3 million per year and total capital costs of USD 6.5 million per year. This was compared to the capital and operating costs of a conventional BHET production process – total operating costs of USD 173.51 million per year total capital costs of USD 38.69 million [57]. As one study reported annual capital costs and the other total costs, it was necessary to calculate total costs for comparison. The total cost was calculated using the capital recovery rate formula [71], taking into account the duration of the project and the interest rate [16].

A review article on mycelial materials [72] was reviewed to obtain an approximate price for the fourth alternative. It presented average prices for mycelium-based materials and compared them with polymer materials. Mycelium-based materials range in price from 0.07 to 0.17 USD/kg, while polymeric materials range in price from 2.1 to 2.3 USD/kg. Average values were used for comparison.

3.2.5. Market demand

All market assessments were collected for the same year, the year 2023, so that they could be compared with each other. The global market for purified terephthalic acid was estimated at USD 78 billion [73]. In the case of bio-oil, it was estimated at USD 10.7 billion in 2023 [74]. The market for construction composites was valued at USD 6.88 billion [75]. The global market size for insulation materials was estimated at USD 65.11 billion [76]. For the third alternative, it was not possible to find market valuations of the BHET crystals. Therefore, PET was considered as it is derived from BHET crystals [16]. In addition, we looked at the recycled cotton market as PET and cotton make up the majority of finished products. The global market for PET was valued at USD 48.43 billion [77] and the market for recycled cotton was valued at USD 5.2 billion [78].

3.2.6. Technology maturity

Only for one of the alternatives did the authors of the reviewed studies assess TRL. This was for the mycelium-based material [27]. They rated this technology within TRL 3. In the first two TRLs the technology concept is developed. In the third level, the proof of concept is tested analytically or experimentally [23]. In the case of mycelium material, it is developed in the laboratory and its properties are tested.

For the other alternatives, the assessment was carried out on the basis of each research paper. The article on the first alternative points out that for the first time it has been reported that hydrothermal liquefaction can process textile waste with mixed composition [8]. For this reason, the technology was assigned TRL 3. The TRC study states that the simple manufacturing process of the resulting material shows its potential to move from the laboratory to pilot scale production [26]. Therefore, it was given a TRL 5 since TRL 6 is the demonstration of a prototype in an appropriate environment [23]. The third alternative is also given a TRL of 3 as the concept is being tested in the laboratory for the first time and process improvements are still needed [16].

3.2.7. Level of research

For the first alternative, the keywords "textile hydrothermal liquefication" were used and the number of publications found was 13. The key words for the second alternative were "textile reinforced composites building" and 138 results were found. For this alternative, we added the additional keywords "AND NOT" with concrete and cement, as several articles appeared at the beginning of the review that were not relevant for the analysis. The search results for the third alternative showed two results using "microwave assisted glycolysis

textile" as the key words. For the last alternative, using "mycelium composite textile" as the key words, 35 results were found.

Only one other study has been carried out on the recycling process and the resulting products of the first alternative. The second study is more recent and uses the same method to process textiles into bio-oil and TPA [79]. Both studies were carried out by the same author. The main difference is that the raw materials were different blends of cotton and polyester.

TRC is relatively well researched. More than 100 results were found, but the first 25 were reviewed. To avoid creating too large a range for the criterion and to reduce the number of articles reviewed, it was decided that the maximum score would be 25. The studies have investigated various composite materials mostly from industrial textile waste [80]–[82], using one [83], [84] or more [85], [86] types of textiles and all of them were designed for the construction industry.

A search for studies similar to the third alternative found only two results, one of which was the article analyzed. The second study that was found focused on textile treatments. It looked at the fabrication of PET textiles with highly durable hydrophilic surfaces through microwave-assisted glycolysis [87]. As the textile is treated rather than recycled, this was not considered relevant. Consequently, there is no similar research work on the third alternative.

A search for studies on mycelium and textiles revealed 35 studies, six of which were relevant to the present case. In many studies, textiles are mentioned because mycelium can be used to make leather like textiles. Two articles were found in which textiles were used as a substrate for fungi cultivation. Ruiz *et al*. developed a mycelium-based composite for the construction industry using denim and agricultural waste [88]. In the second study, biocomposites were developed as alternatives to plastic packaging products using cotton and polyester as feedstock [89]. No additional biomass substrates were added in this study. The other four studies were carried out by the same authors, Jiang et al. on one product type, a biocomposite sandwich [90]–[93]. The resulting material is a multi-layer composite, with all materials of natural origin. It uses natural textile fibers as the skin, mycelium connected agricultural waste as the core and bioresin as the matrix [92].

3.2.8. Market competitiveness

For TPA and bio-oil, yield was chosen as the main characteristic. As mentioned before, the yields achieved in the study were 3–9 % bio-oil and 38–54 % TPA [8]. The most common technology for producing TPA is the Mid-Century process, also known as the AMOCO process. The reaction typically yields 95 % TPA [51]. Typical bio-oil yields from hydrothermal liquefaction range from 24 to 64 % [94].

In the case of TRC, the test results obtained in the study were verified and compared with standard wood particleboard according to ISO 16893:2016 [26]. Thus, it was not necessary to look for the properties of a conventional material. Overall, the material properties were optimal and, in the case of moisture resistance, better than required. They were significantly lower than those required by the standard, indicating high moisture resistance characteristics [26].

Currently, for the third alternative, only one of the resulting products is comparable in quality to the conventional product: BHET crystals with 93 % purity and the possibility to decolorize and obtain ≥99 % purity [16]. The other products need further research and optimization. To increase the selectivity of 4.4′-methylenedianiline, further optimization of the treatment of the spandex monomers is needed. Reactive dyes have remained on cotton and their degree of polymerization has decreased, so further research is needed to obtain better quality. Finally, nylon has a reduced average molecular weight. Therefore, more research is

needed to establish the optimum processing conditions for decolorization and to limit the reduction in molecular weight [16].

Four properties were tested for the mycelium-based material: compressive strength, tensile strength, elastic modulus and thermal conductivity [27]. As it was intended as a thermal insulation material, the thermal conductivity was chosen for comparison. Its thermal conductivity was 1.04±0.17 W/mK for grass cutting and dry leave material and 0.85 ± 0.02 for sugarcane bagasse material W/mK [27]. The authors compared these with the thermal conductivity of other mycelium materials and concluded that the addition of textiles improves this property. However, it is much higher compared to solutions on the market. For example, the thermal conductivity of expanded polystyrene is 0.030–0.045 W/mK [95].

3.2.9. Social aspects

The risks and health impacts from bio-oil and TPA production are assessed as medium (2 points), as there is no direct risk to everyday workers from hazardous chemicals or processes. However, the hydrothermal liquefaction process involves high temperatures and pressures, which pose a risk of burns and explosion [96].

In general, the production of composite materials poses risks from toxic substances and from workers inhaling liquid matrices, vapors from hardeners and solvents, and reinforcement material particles [97]. In the case of the study analyzed, textile and wood dust could pose the greatest risk [26]. Wood dust is a proven human carcinogen [98]. Therefore, the human health risk was assessed as medium.

The chemical recycling process of the third alternative was assessed as the most hazardous of all the alternatives considered. This is due to the chemicals now and potentially later used in recycling processes, such as ethylene glycol [16]. This substance is registered under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and is toxic to humans [99].

The production of a mycelium-based material consists of relatively simple steps [27]. First, the substrate is prepared, the required moisture content and pH level are established and then it is pasteurized. The mushroom spawn is then added, and cultivation begins. At the end of the cultivation, the material undergoes a dehydration process to deactivate the fungi. There are no hazards during the production phase, as no relatively high temperatures and pressures and no hazardous chemicals are used. The mushrooms used are generally not harmful to humans [100]. In the reviewed alternatives case, it was edible mushroom. Another risk to consider is exposure to spores, which can cause health problems such as asthma [101]. However, most people are relatively unaffected unless they have allergies, and most of the time, these health problems are due to mold fungi [101] that are not supposed to be present in the production process of mycelium based material.

3.3. Results of the TOPSIS

After defining the input data, TOPSIS calculations were performed. The results are shown graphically in Fig. 1. According to the MCDA evaluation, the mycelium-based material is the best alternative as it scores the highest (0.63). It achieved four ideal values. This means that the input values met the ideal value conditions for four criteria. The ideal value conditions were the same for all criteria, the maximum value meaning that the best alternative for a given criterion is the one with the highest value. It also had three anti-ideal values. However, the other alternatives had more: bio-oil and TPA (4), TRC (3) and BHET crystals, spandex monomers and cotton and nylon (5). Bio-oil and TPA product group was the only alternative that did not reach any of the ideal values and also had the lowest overall score.
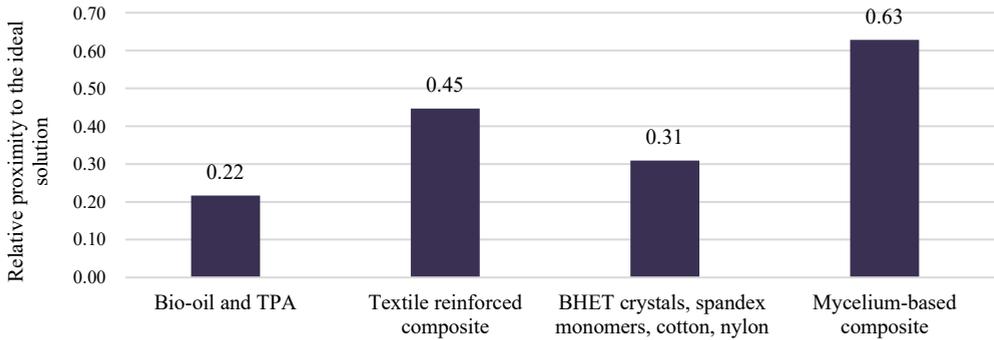
Fig. 1. Resulting rating of alternatives from TOPSIS analysis.

Normalized weighted criteria scores for each alternative are shown in Fig. 2. As can be seen, mycelium-based material has the greatest potential for further development as it is relatively well studied and have a simple manufacturing process. Its economic viability and market potential are very high. The material also has significant environmental advantages and can be produced from a wide range of waste and by-products [102]. The weakness of the product lies in its characteristics compared to the products available on the market. However, only the thermal conductivity was compared in this study. In any case, further research is needed to optimize the product properties and to explore other applications.

The results show that bio-oil and TPA, which scored the lowest, have comparable results to other alternatives in TRL level and in market competitiveness both reflecting technical performance. The alternative has the best performance at market demand. However, it scores lowest in environmental factors. The textile-reinforced composite showed visibly good results on technical aspects and fair results on environmental and social aspects. However, it had a very poor economic performance. Lastly, BHET crystals, spandex monomers and cotton and nylon showed strong results in environmental impact and longevity and recyclability, but this type of recycling is very innovative and needs further research to improve other aspects.
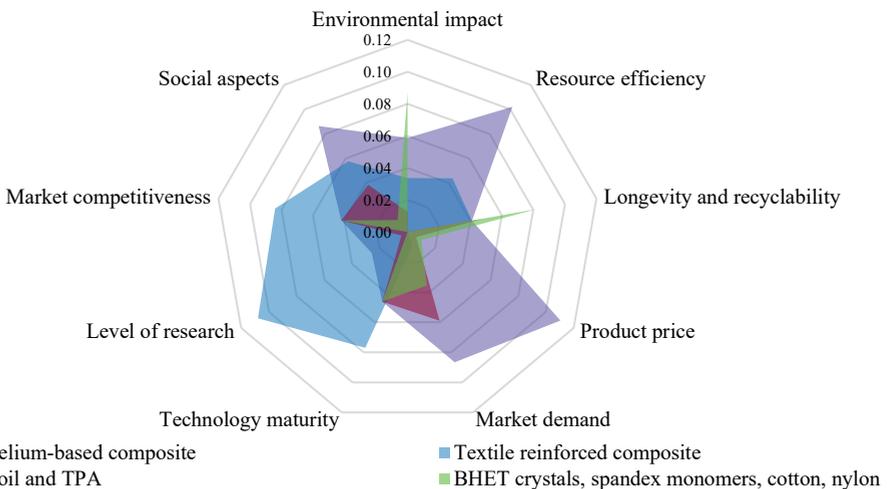

Fig. 2. Normalized weighted scores for all criteria for each alternative.

3.4. Results of the Sensitivity Analysis

A sensitivity analysis is carried out to see how the results respond to changes in the weight or impact of the criteria. The analysis was performed for all criteria. For most criteria, the mycelium-based material maintained its position as the best alternative: in eight out of nine criteria. This indicates that even if the weights were changed in the MCDA analysis, the mycelium-based material would be the best alternative. The only criterion that resulted in the mycelium-based material losing first place was the "Level of Research" (see Fig. 3). If the weight of this criterion were to increase at least 1.5 times, the best alternative would be TRC. This is mainly because TRC is the second best alternative and has been studied considerably more than the other alternatives.
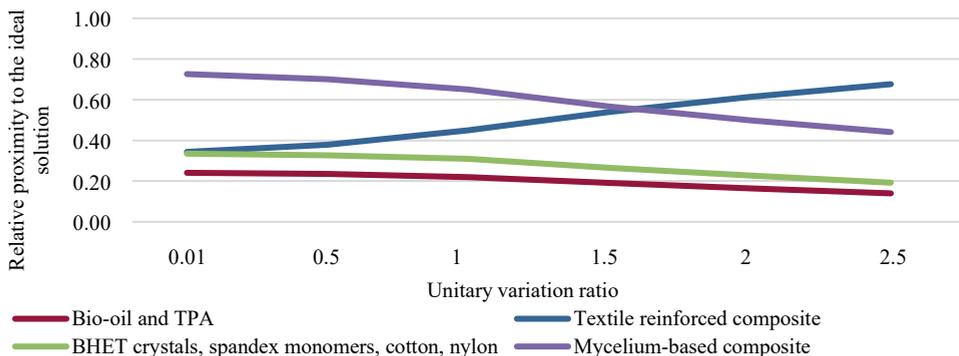

Fig. 3. Results of sensitivity analysis for Level of Research criterion.

4. CONCLUSIONS

The EU is moving towards a circular economy in textiles, but there are several obstacles in the way. Currently, there are no commercially viable technologies to recycle mixed textiles back into textiles or high value-added products. This study therefore looked at what has been researched so far on post-consumer mixed textile recycling and assessed which technology should be further developed based on economic, environmental, social and technical factors.

The literature analysis identified 27 articles on textile recycling. Only 4 of these articles met the requirements - input textiles are mixed and post-consumer. This shows that the topic is not sufficiently researched and that there are not enough technologies under development to recycle mixed post-consumer textiles.

These four products and product groups were further compared using the MCDA. Nine criteria were used. The results showed that the mycelium-based material has the highest potential for further development (0.63). It is relatively well researched, has a simple production process, has a high economic viability and market potential and has significant environmental advantages. The sensitivity analysis showed that mycelium-based material would remain the best alternative in most cases, even if the weights of the criteria were to be changed.

As the comparison of products is based on data found in the literature, further in-depth research is needed before the product can be commercialized. The technical characteristics of the product should be re-examined, an environmental, social, technical and economic assessment should be carried out and only then the product could be tested on a pilot scale.

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REFERENCES

[1] Abrishami S., Shirali A., Sharples N., Kartal G. E., Macintyre L., Doustdar O. Textile Recycling and Recovery: An Eco-friendly Perspective on Textile and Garment Industries Challenges. *Text. Res. J.* 2024:94(23–24):2815–2834. https://doi.org/10.1177/00405175241247806

[2] Ellen MacArthur Foundation. A new textiles economy: Redesigning fashion's future. 2017.

[3] United Nations. The 2030 Agenda for Sustainable Development. [Online]. [Accessed: 20.03.2025]. Available: https://www.un.org/sustainabledevelopment/development-agenda/

[4] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A new Circular Economy Action Plan. Brussels, 2020. [Online]. [Accessed: 13.02.2025]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[5] European Union. Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives. *Official Journal of the European Union*, 2018.

[6] McKinsey & Company. Scaling textile recycling in Europe: Turning waste into value. 2022. [Online]. [Accessed: 17.03.2025]. Available: https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value#/

[7] European Environment Agency. Management of used and waste textiles in Europe's circular economy. In EEA Briefing. LU: Publications Office, 2024. [Online]. [Accessed: 18.03.2025]. Available: https://data.europa.eu/doi/10.2800/229868

[8] Matayeva A., Madsen A. S., Biller P. Evaluation of different fiber impurities on hydrothermal liquefaction of mixed textile waste. *Resour. Conserv. Recycl.* 2023:190:106833. https://doi.org/10.1016/j.resconrec.2022.106833

[9] Seifali Abbas-Abadi M. *et al.* Advancing Textile Waste Recycling: Challenges and Opportunities Across Polymer and Non-Polymer Fiber Types. *Polymers* 2025:17(5):628. https://doi.org/10.3390/polym17050628

[10] Lu L. *et al.* Current recycling strategies and high-value utilization of waste cotton. *Sci. Total Environ.* 2023:856:158798. https://doi.org/10.1016/j.scitotenv.2022.158798

[11] Pensupa N. *et al.* Recent Trends in Sustainable Textile Waste Recycling Methods: Current Situation and Future Prospects. In *Chemistry and Chemical Technologies in Waste Valorization*, Lin C. S. K., Ed., in Topics in Current Chemistry Collections. Cham: Springer International Publishing, 2017:189–228. https://doi.org/10.1007/978-3-319-90653-9_7

[12] Shahid M. A., Raza M., Javed M. A., Khan Z., Ali S., Ahmad I. Prospects and challenges of recycling and reusing post-consumer garments: A review. *Clean. Eng. Technol.* 2024:19:100744. https://doi.org/10.1016/j.clet.2024.100744

[13] Baloyi R. B., Gbadeyan O. J., Sithole B., Chunilall V. Recent advances in recycling technologies for waste textile fabrics: A review. *Text. Res. J.* 2024:94(3–4):508–529. https://doi.org/10.1177/00405175231210239

[14] Wang S., Salmon S. Progress toward Circularity of Polyester and Cotton Textiles. *Sustain. Chem.* 2022:3(3):376–403. https://doi.org/10.3390/suschem3030024

[15] Loo S.-L., Yu E., Hu X. Tackling critical challenges in textile circularity: A review on strategies for recycling cellulose and polyester from blended fabrics. *J. Environ. Chem. Eng.* 2023:11(5):110482. https://doi.org/10.1016/j.jece.2023.110482

[16] Andini E., Bhalode P., Gantert E., Sadula S., Vlachos D. G. Chemical recycling of mixed textile waste. *Sci. Adv.* 2024:10(27):eado6827. https://doi.org/10.1126/sciadv.ado6827

[17] Patel N., Blumberga D. Insights of Bioeconomy: Biopolymer Evaluation Based on Sustainability Criteria. *Environ. Clim. Technol.* 2023:27(1):323–338. https://doi.org/10.2478/rtuect-2023-0025

[18] Valtere M., *et al.* The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran. *Environ. Clim. Technol.* 2022:26(1):658–669. https://doi.org/10.2478/rtuect-2022-0050

[19] Zlaugotne B., Zihare L., Balode L., Kalnbalkite A., Khabdullin A., Blumberga D. Multi-Criteria Decision Analysis Methods Comparison. *Environ. Clim. Technol.* 2020:24(1):454–471. https://doi.org/10.2478/rtuect-2020-0028

[20] Ibáñez-Forés V., Bovea M. D., Pérez-Belis V. A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. *J. Clean. Prod.* 2014:70:259–281. https://doi.org/10.1016/j.jclepro.2014.01.082

[21] Mertzanakis C., Vlachokostas C., Toufexis C., Michailidou A. V. Closing the Loop between Waste-to-Energy Technologies: A Holistic Assessment Based on Multiple Criteria. *Energies* 2024:17(12):2971. https://doi.org/10.3390/en17122971

[22] Levänen J., Uusitalo V., Härri A., Kareinen E., Linnanen L. Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles. *Environ. Res. Lett.* 2021:16(5):054069. https://doi.org/10.1088/1748-9326/abfac3

[23] Mankins J. C. Technology readiness assessments: A retrospective. *Acta Astronaut.* 2009:65(9–10):1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

[24] Ono S., Tsusaka T. W. Comparative Analysis of Environmental, Economic, and Social Criteria for Plastic Recycling Technology Selection in India, Sri Lanka, Pakistan, and Thailand. *Int. J. Sustain. Dev. Plan.* 2023:18(8):2461–2471. https://doi.org/10.18280/ijsdp.180817

[25] Li P., Qian H., Wu J., Chen J. Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights. *Environ. Monit. Assess.* 2013:185(3):2453–2461. https://doi.org/10.1007/s10661-012-2723-9

[26] Echeverria C. A., Handoko W., Pahlevani F., Sahajwalla V. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. *J. Clean. Prod.* 2019:208:1524–1536. https://doi.org/10.1016/j.jclepro.2018.10.227

[27] Gomez T. S., *et al*. Development of a myco-material based on textile and agro-industrial waste for thermal insulation. *E3S Web Conf.* 2024:546:03003. https://doi.org/10.1051/e3sconf/202454603003

[28] Li M., Luo J., Huang Y., Li X., Yu T., Ge M. Recycling of waste poly(ethylene terephthalate) into flame-retardant rigid polyurethane foams. *J. Appl. Polym. Sci.* 2014:131(19):app.40857. https://doi.org/10.1002/app.40857

[29] Sun H., Chen Z., Zhou J., Chen L., Zuo W. Recovery of high-quality terephthalic acid from waste polyester textiles via a neutral hydrolysis method. *J. Environ. Chem. Eng.* 2024:12(3):112558. https://doi.org/10.1016/j.jece.2024.112558

[30] Ravikumar D., Mani P., Bernaurdshaw N., Vajiravelu S. Microwave-Induced Chemical Recycling of Colored Polyester Textile Wastes Promoted by Zn[(L)Proline]₂, as a Recyclable Homogeneous Catalyst. *Waste Biomass Valorization* 2024:15(8):4585–4598. https://doi.org/10.1007/s12649-024-02522-3

[31] Kirstein M., *et al*. Monomer Recycling and Repolymerization of Post-Consumer Polyester Textiles. *Chem. Ing. Tech.* 2023:95(8):1290–1296. https://doi.org/10.1002/cite.202200197

[32] Islam S., Bhat G., Mani S. Life cycle assessment of thermal insulation materials produced from waste textiles. *J. Mater. Cycles Waste Manag.* 2024:26(2):1071–1085. https://doi.org/10.1007/s10163-023-01882-7

[33] Hussain A., Goljandin D., Podgursky V., Abbas M. M., Krasnou I. Experimental mechanics analysis of recycled polypropylene-cotton composites for commercial applications. *Adv. Ind. Eng. Polym. Res.* 2023:6(3):226–238. https://doi.org/10.1016/j.aiepr.2022.11.001

[34] Sanchis-Sebastiá M., Ruuth E., Stigsson L., Galbe M., Wallberg O. Novel sustainable alternatives for the fashion industry: A method of chemically recycling waste textiles via acid hydrolysis. *Waste Manag.* 2021:121:248–254. https://doi.org/10.1016/j.wasman.2020.12.024

[35] Ruuth E., *et al*. Reclaiming the Value of Cotton Waste Textiles: A New Improved Method to Recycle Cotton Waste Textiles via Acid Hydrolysis. *Recycling* 2022:7(4):57. https://doi.org/10.3390/recycling7040057

[36] Cao H., Cobb K., Yatvitskiy M., Wolfe M., Shen H. Textile and Product Development from End-of-Use Cotton Apparel: A Study to Reclaim Value from Waste. *Sustainability* 2022:14(14):8553. https://doi.org/10.3390/su14148553

[37] Singh V., Wyatt J., Zoungrana A., Yuan Q. Evaluation of Vermicompost Produced by Using Post-Consumer Cotton Textile as Carbon Source. *Recycling* 2022:7(1):10. https://doi.org/10.3390/recycling7010010

[38] Opálková Šišková A., *et al.* Reuse of Textile Waste to Production of the Fibrous Antibacterial Membrane with Filtration Potential. *Nanomaterials* 2021:12(1):50. https://doi.org/10.3390/nano12010050

[39] Raj M., Fatima S., Tandon N. Recycled materials as a potential replacement to synthetic sound absorbers: A study on denim shoddy and waste jute fibers. *Appl. Acoust.* 2020:159:107070. https://doi.org/10.1016/j.apacoust.2019.107070

[40] Aman, Tonk D., Shokeen K., Singh D. K. Development of fire retarding composite board for fire compartmentation application using waste denim: A review. *Mater. Today Proc.* 2022:60:259–266. https://doi.org/10.1016/j.matpr.2021.12.513

[41] Vadivel R., Nirmala M., Raji K., Siddaiah B., Ramamurthy P. Synthesis of highly luminescent carbon dots from postconsumer waste silk cloth and investigation of its electron transfer dynamics with methyl viologen dichloride. *J. Indian Chem. Soc.* 2021:98(11):100181. https://doi.org/10.1016/j.jics.2021.100181

[42] Bediako J. K., Wei W., Yun Y.-S. Low-cost renewable adsorbent developed from waste textile fabric and its application to heavy metal adsorption. *J. Taiwan Inst. Chem. Eng.* 2016:63:250–258. https://doi.org/10.1016/j.jtice.2016.03.009

[43] Zhang J., *et al*. Fabrication of leather-like yarns using waste leather for textile application. *Prog. Org. Coat.* 2024:186:108053. https://doi.org/10.1016/j.porgcoat.2023.108053

[44] Haslinger S., Hummel M., Anghelescu-Hakala A., Määttänen M., Sixta H. Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers. *Waste Manag.* 2019:97:88–96. https://doi.org/10.1016/j.wasman.2019.07.040

[45] Xia G., *et al.* Complete recycling and valorization of waste textiles for value-added transparent films via an ionic liquid. *J. Environ. Chem. Eng.* 2021:9(5):106182. https://doi.org/10.1016/j.jece.2021.106182

[46] Apostolopoulou-Kalkavoura V., Fijoł N., Lombardo S., Ruiz-Caldas M., Mathew A. P. In Situ Functionalisation and Upcycling of Post-Consumer Textile Blends into 3D Printable Nanocomposite Filaments. *Adv. Sustain. Syst.* 2024:8(9):2400132. https://doi.org/10.1002/adsu.202400132

[47] Hu Y., Du C., Pensupa N., Lin C. S. K. Optimisation of fungal cellulase production from textile waste using experimental design. *Process Saf. Environ. Prot.* 2018:118:133–142. https://doi.org/10.1016/j.psep.2018.06.009

[48] Mihalyi S., *et al.* Simultaneous saccharification and fermentation with *Weizmannia coagulans* for recovery of synthetic fibers and production of lactic acid from blended textile waste. *Resour. Conserv. Recycl.* 2023:196:107060. https://doi.org/10.1016/j.resconrec.2023.107060

[49] El Wazna M., El Fatihi M., El Bouari A., Cherkaoui O. Thermo physical characterization of sustainable insulation materials made from textile waste. *J. Build. Eng.* 2017:12:196–201. https://doi.org/10.1016/j.jobe.2017.06.008

[50] Çay A., Yanık J., Akduman Ç., Duman G., Ertaş H. Application of textile waste derived biochars onto cotton fabric for improved performance and functional properties. *J. Clean. Prod.* 2020:251:119664. https://doi.org/10.1016/j.jclepro.2019.119664

[51] Lapa H. M., Martins L. M. D. R. S. p-Xylene Oxidation to Terephthalic Acid: New Trends. *Molecules* 2023:28(4):1922. https://doi.org/10.3390/molecules28041922

[52] Guo G., He Y., Jin F., Mašek O., Huang Q. Application of life cycle assessment and machine learning for the production and environmental sustainability assessment of hydrothermal bio-oil. *Bioresour. Technol.* 2023:379:129027. https://doi.org/10.1016/j.biortech.2023.129027

[53] Ecoinvent 3.10. Crude 'petroleum' oil. RoW market for petroleum.

[54] Gian M., García-Velásquez C., Van Der Meer Y. Comparative life cycle assessment of the biochemical and thermochemical production routes of biobased terephthalic acid using *Miscanthus* in the Netherlands. *Clean. Environ. Syst.* 2022:6:100085. https://doi.org/10.1016/j.cesys.2022.100085

[55] Arya M., Skrifvars M., Khalili P. Performance and life cycle assessment of composites reinforced with natural fibers and end-of-life textiles. *J. Compos. Sci.* 2024:8(6):196. https://doi.org/10.3390/jcs8060196

[56] Ecoinvent 3.10. Glass fibre reinforced plastic, polyamide, injection moulded GLO. Market for glass fibre reinforced plastic, polyamide, injection moulded.

[57] Luo Y., Selvam E., Vlachos D. G., Ierapetritou M. Economic and environmental benefits of modular microwave-assisted polyethylene terephthalate depolymerization. *ACS Sustain. Chem. Eng.* 2023:11(10):4209–4218. https://doi.org/10.1021/acssuschemeng.2c07203

[58] Volk R., *et al.* Life cycle assessment of mycelium-based composite materials. *Resour. Conserv. Recycl.* 2024:205:107579. https://doi.org/10.1016/j.resconrec.2024.107579

[59] Elsacker E., Vandelook S., Van Wylick A., Ruytinx J., De Laet L., Peeters E. A comprehensive framework for the production of mycelium-based lignocellulosic composites. *Sci. Total Environ.* 2020:725:138431. https://doi.org/10.1016/j.scitotenv.2020.138431

[60] Panwar N. L., Paul A. S. An overview of recent development in bio-oil upgrading and separation techniques. *Environ. Eng. Res.* 2020:26(5):200382–0. https://doi.org/10.4491/eer.2020.382

[61] Valtere M., Bezrucko T., Blumberga D. Analysis of textile circularity potential. *Environ. Clim. Technol.* 2023:27(1):220–232. https://doi.org/10.2478/rtuect-2023-0017

[62] Borjan D., Knez Ž., Knez M. Recycling of carbon fiber-reinforced composites – Difficulties and future perspectives. *Materials* 2021:14(15):4191. https://doi.org/10.3390/ma14154191

[63] De Fazio D., Boccarusso L., Formisano A., Viscusi A., Durante M. A review on the recycling technologies of fibre-reinforced plastic (FRP) materials used in industrial fields. *J. Mar. Sci. Eng.* 2023:11(4):851. https://doi.org/10.3390/jmse11040851

[64] Bahramian M., Yetilmezsoy K. Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy Build.* 2020:219:109917. https://doi.org/10.1016/j.enbuild.2020.109917

[65] Alaneme K. K., *et al.* Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Alex. Eng. J.* 2023:83:234–250. https://doi.org/10.1016/j.aej.2023.10.012

[66] Egan J., Salmon S. Strategies and progress in synthetic textile fiber biodegradability. *SN Appl. Sci.* 2022:4(1):22. https://doi.org/10.1007/s42452-021-04851-7

[67] Singh A., *et al.* Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate). *Joule* 2021:5(9):2479–2503. https://doi.org/10.1016/j.joule.2021.06.015

[68] Mahmood R., Parshetti G. K., Balasubramanian R. Energy, exergy and techno-economic analyses of hydrothermal oxidation of food waste to produce hydro-char and bio-oil. *Energy* 2016:102:187–198. https://doi.org/10.1016/j.energy.2016.02.042

[69] Suriani M. J., *et al*. Critical review of natural fiber reinforced hybrid composites: Processing, properties, applications and cost. *Polymers* 2021:13(20):3514. https://doi.org/10.3390/polym13203514

[70] Silicone coated glass fiber woven roving fiberglass reinforced composite material from factory for composite materials. [Online]. [Accessed: 13.01.2025]. Available: https://www.alibaba.com/product-detail/Silicone-Coated-Glass-Fiber-Woven-Roving_60112675930.html

[71] Hashemi A., Derakhshan G., Alizadeh Pahlavani M. R., Abdi B. Techno-economic analysis of a stand-alone hybrid wind-power fuel-cell grid system: A case study in Shahryar region of Tehran. *Environ. Clim. Technol.* 2020:24(1):691–705. https://doi.org/10.2478/rtuect-2020-0043

[72] Alemu D., Tafesse M., Mondal A. K. Mycelium-based composite: The future sustainable biomaterial. *Int. J. Biomater.* 2022:2022(1). https://doi.org/10.1155/2022/8401528

[73] Verified Market Reports. Global purified terephthalic acid (PTA) market by type (Type 1, Type 2), by application (Polyester, Polybutylene Terephthalate (PBT)), by geographic scope and forecast. [Online]. [Accessed: 18.12.2024]. Available: https://www.verifiedmarketreports.com/product/purified-terephthalic-acid-pta-market/

[74] Verified Market Reports. Global bio-oil market by type (Bioethanol, Biodiesel), by application (Industrial fuels, Transportation fuels), by geographic scope and forecast. [Online]. [Accessed: 18.12.2024]. Available: https://www.verifiedmarketreports.com/product/bio-oil-market/

[75] Starits Research. Construction composites market size, share & trends analysis report. [Online]. [Accessed: 18.12.2024]. Available: https://straitsresearch.com/report/construction-composites-market

[75] Starits Research. Construction Composites Market Size, Share & Trends Analysis Report by Resin. Forecasts, 2024–2032. [Online]. [Accessed: 18.12.2024]. Available: https://straitsresearch.com/report/construction-composites-market

[76] GVR. Insulation Market Size, Share & Trends Analysis Report by Product (Glass Wool, Mineral Wool, EPS, XPS, CMS Fibers), By End-use (Construction, Industrial, HVAC & OEM), By Region, And Segment Forecasts, 2024–2030. [Online]. [Accessed: 18.12.2024]. Available: https://www.grandviewresearch.com/industry-analysis/insulation-market

[77] FORTUNE. Polyethylene Terephthalate (PET) Market Size, Share & Industry Analysis, By Type (Virgin and Recycled), Application (Rigid Packaging, Film, Sheets & Straps, and Others), and Regional Forecast, 2024–2032. [Online]. [Accessed: 20.12.2024]. Available: https://www.fortunebusinessinsights.com/industry-reports/polyethylene-terephthalate-pet-market-101743

[78] DATAINTELO. Recycled Cotton Yarn Market. [Online]. [Accessed: 21.12.2024]. Available: https://dataintelo.com/report/global-recycled-cotton-yarn-market

[79] Matayeva A., Biller P. Hydrothermal liquefaction of post-consumer mixed textile waste for recovery of bio-oil and terephthalic acid. *Resour. Conserv. Recycl.* 2022:185:106502. https://doi.org/10.1016/j.resconrec.2022.106502

[80] Sulochani R. M. N., Jayasinghe R. A., Priyadarshana G., Nilmini A. H. L. R., Ashokcline M., Dharmaratne P. D. Waste-based composites using post-industrial textile waste and packaging waste from the textile manufacturing industry for non-structural applications. *Sustain. Chem. Environ.* 2024:8:100163. https://doi.org/10.1016/j.scenv.2024.100163

[81] Mohan S., Thilagavathi G., Rajkhowa R. Development of micro dust reinforced composite for building applications. *J. Clean. Prod.* 2024:470:143244. https://doi.org/10.1016/j.jclepro.2024.143244

[82] Kamble Z., Behera B. K. Sustainable hybrid composites reinforced with textile waste for construction and building applications. *Constr. Build. Mater.* 2021:284:122800. https://doi.org/10.1016/j.conbuildmat.2021.122800

[83] Rakhsh Mahpour A., Ventura H., Ardanuy M., Rosell J. R., Claramunt J. The effect of fibres and carbonation conditions on the mechanical properties and microstructure of lime/flax composites. *Cem. Concr. Compos.* 2023:138:104981. https://doi.org/10.1016/j.cemconcomp.2023.104981

[84] Suthatho A., Rattanawongkun P., Tawichai N., Tanpichai S., Boonmahitthisud A., Soykeabkaew N. Low-density all-cellulose composites made from cotton textile waste with promising thermal insulation and acoustic absorption properties. *ACS Appl. Polym. Mater.* 2024:6(1):390–397. https://doi.org/10.1021/acsapm.3c02076

[85] Kamble Z., Behera B. K. Fabrication and performance evaluation of waste cotton and polyester fiber-reinforced green composites for building and construction applications. *Polym. Compos.* 2021:42(6):3025–3037. https://doi.org/10.1002/pc.26036

[86] Dev B., Rahman M. A., Tazrin T., Islam M. S., Datta A., Rahman M. Z. Investigation of mechanical properties of nonwoven recycled cotton/PET fiber-reinforced polyester hybrid composites. *Macromol. Mater. Eng.* 2024:309(6):2400020. https://doi.org/10.1002/mame.202400020

[87] Zhou W., Huang H., Du S., Wang Q., He J., Cui S. Facile fabrication of polyester filament fabric with highly and durable hydrophilic surface by microwave-assisted glycolysis. *J. Appl. Polym. Sci.* 2016:133(40):app.44069. https://doi.org/10.1002/app.44069

[88] Ruiz A., Cogdell C., Mak J., Rowe A., Wan S., La Saponara V. Valorization and biorefinery of local agricultural and textile wastes through mycelium composites for structural applications. *Res. Dir. Biotechnol. Des.* 2024:2:e10. https://doi.org/10.1017/btd.2024.8

[89] Saini R., Kaur G., Brar S. K. Textile residue-based mycelium biocomposites from *Pleurotus ostreatus*. *Mycology* 2024:15(4):683–689. https://doi.org/10.1080/21501203.2023.2278308

[90] Jiang L., Walczyk D., McIntyre G. A new approach to manufacturing biocomposite sandwich structures: Investigation of preform shell behavior. *J. Manuf. Sci. Eng.* 2017:139(2):021014. https://doi.org/10.1115/1.4034278

[91] Jiang L., Walczyk D., McIntyre G., Bucinell R., Li B. Bioresin infused then cured mycelium-based sandwich-structure biocomposites: Resin transfer molding (RTM) process, flexural properties, and simulation. *J. Clean. Prod.* 2019:207:123–135. https://doi.org/10.1016/j.jclepro.2018.09.255

[92] Jiang L., Walczyk D., McIntyre G., Bucinell R., Tudryn G. Manufacturing of biocomposite sandwich structures using mycelium-bound cores and preforms. *J. Manuf. Process.* 2017:28:50–59. https://doi.org/10.1016/j.jmapro.2017.04.029

[93] Jiang L., Walczyk D. F., Li B. Modeling of glue penetration into natural fiber reinforcements by roller infusion. *J. Manuf. Sci. Eng.* 2018:140(4):041006. https://doi.org/10.1115/1.4038514

[94] Nagappan S., *et al.* Catalytic hydrothermal liquefaction of biomass into bio-oils and other value-added products – A review. *Fuel* 2021:285:119053. https://doi.org/10.1016/j.fuel.2020.119053

[95] InsulationGo. What is thermal conductivity? [Online]. [Accessed: 16.01.2024]. Available: https://insulationgo.co.uk/thermal-conductivity/

[96] Lowry P. P., Wagner K. A. Hydrothermal liquefaction treatment hazard analysis report. PNNL--24219 Rev 3, 1406834. Sep. 2016. https://doi.org/10.2172/1406834

[97] Asmatulu E., Alonayni A., Alamir M. Safety concerns in composite manufacturing and machining. In: Naguib H. E., ed. *Behavior and Mechanics of Multifunctional Materials and Composites XII.* Denver, United States: SPIE; Mar. 2018:68. https://doi.org/10.1117/12.2296707

[98] Beigzadeh Z., Pourhassan B., Kalantary S., Golbabaei F. Occupational exposure to wood dust and risk of nasopharyngeal cancer: A systematic review and meta-analysis. *Environ. Res.* 2019:171:170–176. https://doi.org/10.1016/j.envres.2018.12.022

[99] European Chemicals Agency (ECHA). Ethane-1,2-diol. [Online]. [Accessed: 19.01.2025]. https://echa.europa.eu/lv/substance-information/-/substanceinfo/100.003.159

[100] Balaeş T., Radu B.-M., Tănase C. Mycelium-composite materials – A promising alternative to plastics? *J. Fungi* 2023:9(2):210. https://doi.org/10.3390/jof9020210

[101] Baxi S. N., *et al.* Exposure and health effects of fungi on humans. *J. Allergy Clin. Immunol. Pract.* 2016:4(3):396–404. https://doi.org/10.1016/j.jaip.2016.01.008

[102] Higgins C., Margot H., Warnquist S., Obeysekare E., Mehta K. Mushroom cultivation in the developing world: A comparison of cultivation technologies. In: *2017 IEEE Global Humanitarian Technology Conference (GHTC).* San Jose, 2017:1–7

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