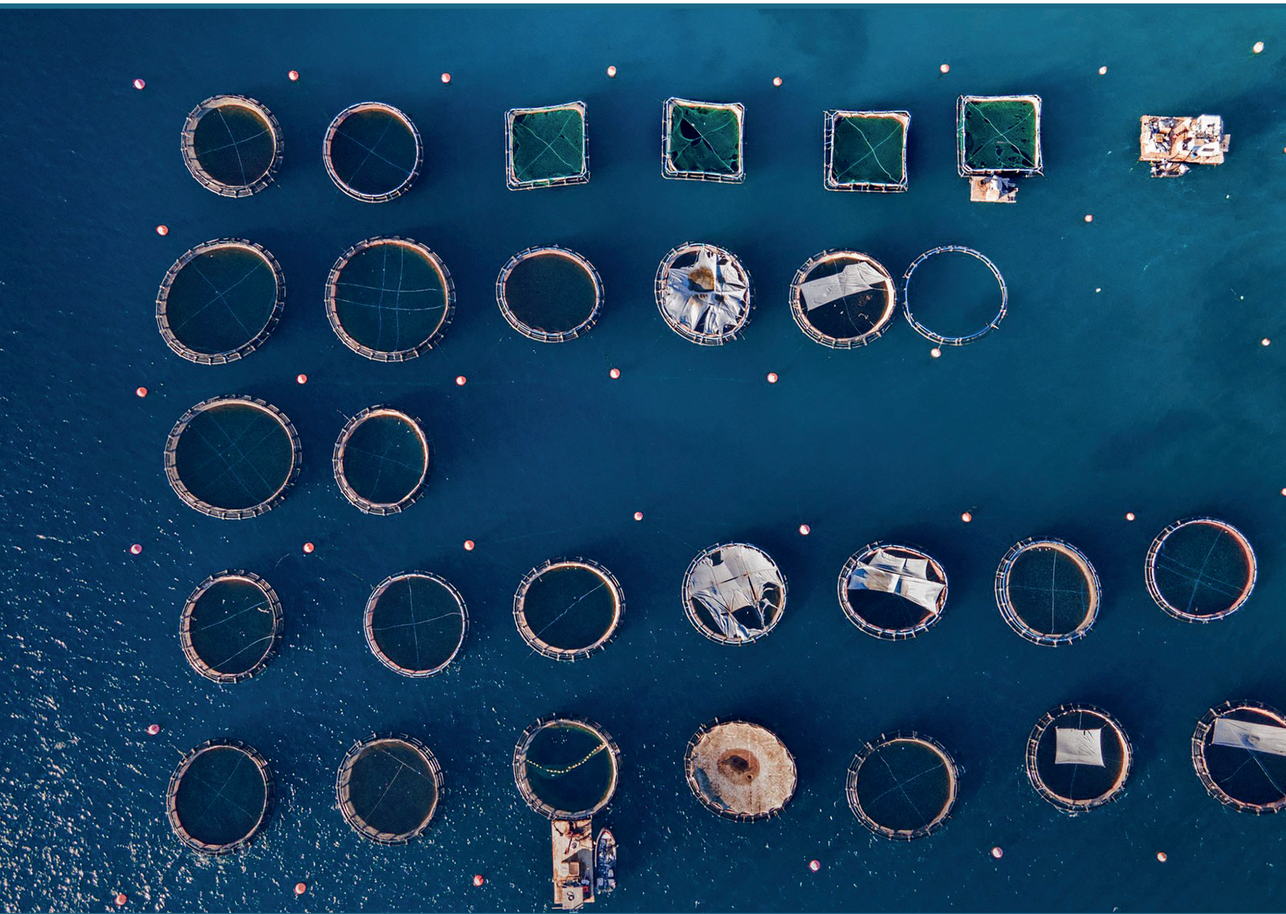
1862

RIGA TECHNICAL UNIVERSITY

Fabian Andres Diaz Sanchez

SUSTAINABILITY IN FOOD SUPPLY CHAINS: A LIFE CYCLE PERSPECTIVE

Summary of the Doctoral Thesis



RTU Press
Riga 2025

RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

Fabian Andres Diaz Sanchez
Doctoral Student of the Doctoral Study Programme "Environmental Engineering"

SUSTAINABILITY IN FOOD SUPPLY CHAINS: A LIFE CYCLE PERSPECTIVE

Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. sc. ing.
FRANCESCO ROMAGNOLI

RTU Press
Riga 2025

Diaz S., F. A. Sustainability in Food Supply Chains: A Life Cycle Perspective. Summary of the Doctoral Thesis. Riga: RTU Press, 2025. 70 p.

Published in accordance with the decision of the Promotion Council "RTU P-19" of 26 June 2024, No. 207.

Picture by *Milos Bicanski / Climate Visuals*.

https://doi.org/10.7250/9789934372254

ISBN 978-9934-37-225-4 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph.D), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on 27th November 2025 at 14:00 at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12/1.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Gatis Bažbauers
Riga Technical University

Professor Dr. sc. Andrea Capelli
Sapienza University of Rome, Italy

Professor Dr. sc. Giuseppe Tomasoni
University of Brescia, Italy

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph.D) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Fabian Andres Diaz Sanchez……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of Introduction, 4 chapters; Conclusions, 47 figures, 12 tables, 7 appendices; the total number of pages is 108, not including appendices. The Bibliography contains 241 titles.

NOMENCLATURE

FSC	Food Supply Chain
EPD	Environmental Product Declaration
CSRD	Corporate Sustainability Reporting Directive
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
LCC	Life Cycle Costing
S-LCA	Social Life Cycle Assessment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
ICCEE	Improving Cold Chain Energy Efficiency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
SDGs	Sustainable Development Goals
SCM	Supply Chain Management
KPI	Key Performance Indicator
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
TfS	Together for Sustainability
ESG	Environmental, Social, and Governance
CSR	Corporate Social Responsibility
GHG	Green House Gases
CDP	Carbon Disclosure Project
SME	Small and Medium Enterprises
CFC	Chlorofluorocarbons
ODP	Ozone Depletion Potential
HCFC	Hydrochlorofluorocarbons
GWP	Global Warming Potential
LCST	Life Cycle Sustainability Tool
LCSA	Life Cycle Sustainability Assessment
C-LCC	Conventional Life Cycle Costing
E-LCC	Environmental Life Cycle Costing
S-LCC	Societal Life Cycle Costing
EoL	End-of-Life
ABC	Activity-Based Costing
FW	Food Waste
EEM	Energy Efficiency Measures
FU	Functional Unit
PCR	Product Category Rules
AD	Anaerobic Digestion
CHP	Combined Heat and Power
DOC	Degradable Organic Content
SETAC	Society of Environmental Toxicology and Chemistry
CED	Cumulated Energy Demand
SNPV	Social Net Present Value
SCBA	Social Cost-Benefit Analysis

CONTENTS

Nomenclature 4
1. Introduction 7
1.1. Research hypothesis..8
1.2. Objectives and Tasks 9
1.3. Scientific novelty..9
1.4. Practical significance 10
1.5. Scope and limitations..11
1.6. Research Framework 12
1.7. Approbation of the results of the research 14
1.8. Other scientific publications..14
1.9. Participation in Conferences 15
1.10. Supervised and Co-supervised Master Thesis..15
2. Literature Review And Research Need..16
2.1. Sustainability concept 16
2.2. Sustainability in food supply chains 17
2.3. Overview of Sustainability Methods in Food Supply Chains 18
2.3.1. Content Analysis. 19
2.3.2. Industry-level sustainability evaluation methods 20
2.4. Food Supply Chain Considerations 21
2.4.1. Additional Sustainability Considerations 21
2.5. Research gaps 22
3. Methodology 24
3.1. Research methods..25
3.1.1. PRISMA Protocol..25
3.1.2. Environmental LCA 26
3.1.3. Life Cycle Costing..26
3.1.4. Social LCA and its challenges 28
3.1.5. Life Cycle Sustainability Assessment 29
4. Results and Discussion 33
4.1. Case studies description and main results..33
4.1.1. Beef Supply Chain..33
4.1.2. Fish Supply Chain 36
4.1.3. Eggs Supply Chain 39
4.1.4. Sustainability evaluation of food waste valorization..42
4.2. Summary of different scenarios 45
5. Life Cycle Sustainability tool..47
5.1.1. LCA output indicators 48
5.1.2. LCC output indicators..49
5.1.3. S-LCA (S-LCC) output indicators 50
5.1.4. Data collection procedure 50
5.1.5. Data input..51
5.1.6. LCA data processing and results visualization 51
5.1.7. LCC modeling..53
5.2. Tool validation 55

6. Conclusions and recommendations 57
6.1. Conclusions related to the objectives 57
6.2. Recommendations 58
6.3 Recommendations for Future Research 58
BIBLIOGRAPHY 60

1. INTRODUCTION

Sustainability has emerged as a pivotal theme in the discourse of environmental conservation and economic development in the contemporary era of rapid globalization and technological advancement. This notion, deeply rooted in the understanding that we inhabit a finite planet with limited resources, has evolved significantly in recent decades. The Brundtland report defined sustainable development as *"the ability to meet present human needs without compromising the ability of future generations to meet their own"*. However, the journey from this foundational understanding to the application in specific sectors such as food supply chains is complex and filled with nuanced challenges.

The food industry, a critical player in the global economy, exemplifies the intricate interplay between economic growth, environmental stewardship, and social equity. The challenges in this sector range from carbon emissions and resource utilization to food safety and waste management, all exacerbated by the globalization-driven elongation of food supply chains (FSCs). As international organizations and technological innovations strive to mitigate these impacts, a coherent, quantitative approach to sustainability assessment in the FSC becomes imperative.

Despite the acknowledgment of sustainability's importance in various industries, methodologies for its assessment often need more contextual depth and overlook key sustainability attributes. While crucial, the prevalent focus on financial dimensions overshadows the even more significant environmental and social aspects. Tools like Environmental Product Declarations (EPDs) and frameworks like the Corporate Sustainability Reporting Directive (CSDR) are attempts to close these gaps. Yet, they often need to improve in delivering a holistic picture of a product's or a company's sustainability.

Despite the progress made, assessing sustainability within FSCs presents unique challenges. Traditional methods often need to capture the full scope of environmental, economic, and social impacts. For instance, while raising consumer awareness, carbon labeling and food miles initiatives offer a limited perspective, focusing primarily on the environmental footprint and overlooking other crucial sustainability dimensions. Similarly, efforts to reduce food losses and waste, though beneficial, still need to fully address the broader implications for social equity and economic development.

Research trends in FSC sustainability have predominantly employed qualitative approaches, with case studies being a standard methodological tool. These studies provide valuable insights into various sustainability issues, including supplier management and sustainable development strategies. However, they often need a consistent theoretical framework, reflecting the growing state of this research field. Moreover, there is a pressing need for more in-depth investigations, particularly in developing countries, where inefficiencies in infrastructure and logistics can exacerbate food waste (FW) and undermine sustainability efforts.

In response to these challenges, there has been an emerging consensus on the need for holistic, multidimensional approaches to sustainability assessment in FSCs. These approaches advocate for integrating both "hard" quantitative methods like Life Cycle Assessment (LCA) and "soft" qualitative methods to ensure a comprehensive understanding of sustainability impacts. This blend of methodologies is crucial for addressing often-overlooked aspects such as human health and the interconnectedness of dietary choices and environmental outcomes.

This Thesis posits that while well-intentioned, the current approach to sustainability assessment in the food supply chain needs to be more cohesive and comprehensive. It contends that there is a conspicuous absence of a standardized, quantifiable methodology that integrates the multifaceted nature of sustainability, encompassing both environmental, economic, and social dimensions. This research aims to architect a holistic, adaptable model for the food supply chain spectrum by dissecting current methodologies and highlighting the disparities in sustainability evaluation. This endeavor is academically significant and crucial for policymakers and industry leaders in bridging the gap between theoretical sustainability concepts and actionable, impactful measures.

In summary, the urgency of this research is underscored by the escalating demands on the food industry to align with sustainable practices amid global environmental challenges. It advances the premise that a comprehensive, quantitatively driven methodology is essential for a genuine sustainability transformation in food supply chains.

1.1. Research hypothesis

This Doctoral Thesis hypothesizes that operationalizing life cycle thinking (LCT) through an integrated framework, encompassing environmental LCA, life cycle costing (LCC), and social life cycle assessment (S-LCA) dimensions, enables a quantitative, standardized, and sector-specific evaluation of sustainability in food supply chains (FSCs). By addressing current methodological gaps, the proposed approach moves beyond fragmented assessments and provides a universally applicable, yet adaptable methodology tailored to the unique operational and contextual features of the food industry.

Specifically, the Thesis tests the following hypotheses:

- Hypothesis 1 (H1): An integrated LCT framework can systematically identify sustainability hotspots and intervention opportunities across different stages of FSCs, enabling the implementation of targeted measures such as energy efficiency improvements and side-stream valorization that can potentially reduce environmental impacts while maintaining economic viability.
- Hypothesis 2 (H2): The life cycle sustainability tool (LCST), developed within this research, provides a scalable, transparent, and decision-oriented mechanism to operationalize the LCT framework. By generating standardized environmental, economic, and social performance indicators, complemented with economic outputs (e.g., net present value, internal rate of return), the tool supports evidence-based decision-making across both large corporations and SMEs.
- Hypothesis 3 (H3): The application of the LCST in real-world case studies (beef, fish, and egg cold chains) validates its practical feasibility and effectiveness, demonstrating its capacity to produce consistent and actionable sustainability insights that contribute to circularity, efficiency, and alignment with EU and global sustainability goals.

In summary, the Thesis postulates that operationalizing life cycle thinking through a customized tool can enable consistent, actionable sustainability assessments in the food industry, contributing to a more circular, efficient, and environmentally responsible supply chain system.

1.2. Objectives and tasks

The main aim of this study is to develop and validate a comprehensive life cycle thinking-based methodology for the standardized, quantitative sustainability evaluation of food supply chains. To achieve this aim, the study pursues the following objectives and tasks:

- Investigate current sustainability assessment methods in the food sector, paying particular emphasis to food supply chains to identify methodological and practical gaps, barriers to usability, and opportunities for integrating environmental, social, and economic pillars.
- Tailor and design an LCT-based framework to address sustainability's environmental, social, and economic dimensions, specifically contextualized for food supply chains.
- Apply the LCT methodology to selected case studies within the food industry (e.g., beef, fish, fruits, waste, eggs) to test assessing its ability to capture sustainability trade-offs across diverse supply chain configurations.
- Interpretation of LCT-based methodology to identify key sustainability hotspots in the food supply chain that help analyze and reduce environmental impacts, minimize food loss, and enhance food quality at consumer endpoints, thus improving the overall sustainability of the supply chain.
- Develop and validate an LCT decision-support tool designed to be user-friendly and industry-oriented, providing insights into the environmental footprint and economic and social performance, enabling knowledge transfer from academia to industry and supporting decision-makers in implementing sustainability strategies in real-world supply chains.

1.3. Scientific novelty

This Doctoral Thesis advances sustainable supply chain management by moving beyond the established conceptual importance of sustainability and life cycle thinking, focusing instead on operationalizing these principles into a practical, quantifiable, and industry-specific framework for the food sector. The research introduces a life cycle sustainability (LCS) framework that integrates environmental (LCA), economic (LCC), and social (S-LCA) dimensions into a single multidisciplinary method, validated through real-world case studies.

The scientific novelty of this study lies in its ability to bridge the gap between theoretical sustainability models and their practical implementation. Despite the existing fragmented or overly simplistic approaches, the proposed framework delivers a universally applicable yet user-friendly tool that enables both large corporations and small and medium-sized enterprises (SMEs) to consistently evaluate and improve sustainability performance with an emphasis on the food supply chains.

By providing key insights for supply chain actors and policymakers, the framework supports applications at both regional and global levels. Thus, the scientific contribution of this research is the creation of a quantifiable, transferable, and comprehensive sustainability framework for food supply chains. This approach not only advances global environmental and social goals but also transforms established concepts into an actionable decision-support tool capable of driving measurable changes in industry practice.

1.4. Practical significance

This Thesis contributes novelty by transforming established life cycle thinking principles into a practical, user-friendly framework that enables consistent sustainability assessment in food supply chains.

More specifically, this Thesis delivers tangible practical value by bridging the gap between academic research and real-world application in sustainable food supply chain management. The developed LCST, grounded in a comprehensive LCT framework, has been validated through empirical case studies in beef, fish, and egg cold chains. These applications developed within the Thesis demonstrate the tool's ability to identify high-impact stages of the supply chain, quantify environmental burdens, and evaluate the cost-effectiveness of energy efficiency measures such as anaerobic digestion and renewable energy integration.

In practical terms, the proposed LCST enables supply chain managers and decision-makers to model different scenarios, compare environmental and economic trade-offs, and prioritize interventions based on quantifiable sustainability performance. For instance, in the Latvian fish cold chain case, the tool facilitated the identification of energy efficiency measures with the potential to deliver lower environmental impacts and improved the internal rate of return

Moreover, the tool's design enables adaptation across diverse food sectors and geographies, making it relevant for policy actors, especially under emerging EU sustainability directives and Corporate Sustainability Reporting requirements. Its transparent output indicators and user-friendly interface make it accessible to small and medium-sized enterprises (SMEs), addressing a common limitation in existing LCA software.

Beyond industry use, the methodological framework and case findings serve as a rich resource for educational programs in environmental engineering, sustainability analytics, and supply chain management. The tool has already been incorporated into master's theses projects at Riga Technical University, supporting student-led sustainability evaluations in real-life industrial contexts.

Overall, the Thesis contributes a validated, scalable, and adaptable solution to the complex challenge of integrating sustainability into food supply chains – with demonstrable impacts at the operational, strategic, and educational levels.

1.5. Scope and limitations

This Thesis focuses on developing a quantitative framework for assessing sustainability in FSCs using life cycle thinking tools. The scope of this research encompasses:

- Analysis of existing sustainability assessment models: A comprehensive review and critique of current models and methodologies in assessing FSC sustainability.
- Development of a quantitative framework: Crafting a novel framework that integrates environmental, economic, and social dimensions of sustainability in a quantifiable manner, specifically tailored to the unique characteristics of FSCs.
- Case studies in specific FSC sectors: Applying the developed framework to selected case studies within the FSC, covering stages such as agriculture, processing, distribution, and retail, to illustrate its applicability and effectiveness.
- Consideration of diverse geographical contexts: While the research will aim to be globally relevant, particular attention will be given to European supply chains, considering data availability and the significance of the food supply chain in those areas.

While this study aims to contribute significantly to the field of sustainability in FSCs, certain limitations are inherent in its scope and methodology.

- Data availability and reliability: The accuracy and comprehensiveness of the sustainability assessment are contingent upon the availability and reliability of data across different stages of the FSC.
- Methodological constraints: The complexity of integrating various sustainability dimensions into a single quantitative framework may pose challenges, particularly in balancing depth and breadth of analysis.
- Generalizability: While the framework developed in this research aims to be adaptable across various sectors of the FSC, its applicability may vary depending on specific industry characteristics and geographical contexts.
- Temporal scope: The research will focus on current and recent data; thus, long-term sustainability trends and future projections may not be fully captured.
- Interdisciplinary challenges: Given the interdisciplinary nature of sustainability assessment, spanning environmental science, economics, and social sciences, synthesizing these diverse perspectives into a cohesive framework presents inherent challenges.

The defined scope and acknowledged limitations of this research serve to clarify the boundaries and expectations of the study. They provide a framework for the research, ensuring a focused and realistic approach to understanding and improving sustainability in food supply chains.

1.6. Research framework

This Doctoral Thesis employs a structured research framework that transforms the conceptual foundations of life cycle thinking (LCT) into a practical, operational methodology tailored to the food industry. The framework follows a logical sequence: starting with an evaluation of existing sustainability assessment practices, moving through the development and application of a new methodology, and concluding with both theoretical advancements and practical contributions. Part of the framework was developed during the author's participation in the *Improving Cold Chain Energy Efficiency (ICCEE)* project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 847040. This collaboration enriched the methodological design and strengthened the empirical dimension of the study through direct industry engagement.

The Thesis is structured into five research steps, which sequentially cover the literature review, methodology development, case study applications, results and discussion, and final conclusions with recommendations. Each chapter builds on the previous one, ensuring a coherent progression from the identification of research gaps to the validation and refinement of the proposed methodology. This structure guarantees both theoretical depth and practical relevance, culminating in a comprehensive understanding of the implications for sustainable food supply chain management.

Figure 1.1 provides an overview of the research framework, highlighting the connections between research objectives and the top-down methodological approach [1]. This visual representation underscores the systematic and rigorous nature of the study, as well as its focus on addressing critical challenges in sustainability evaluation.

The methodological choices were informed by a comprehensive literature review that identified state-of-the-art approaches for quantitative sustainability assessment. These include life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA), complemented by recognised impact assessment models and international standards (e.g., ISO 14040/44 and UNEP guidelines). A concise description of these methods is provided in Chapter 3, while their integration and application are demonstrated in the empirical chapters. For a more detailed discussion of their theoretical underpinnings and practical implications, reference should be made to the full text of the Thesis.

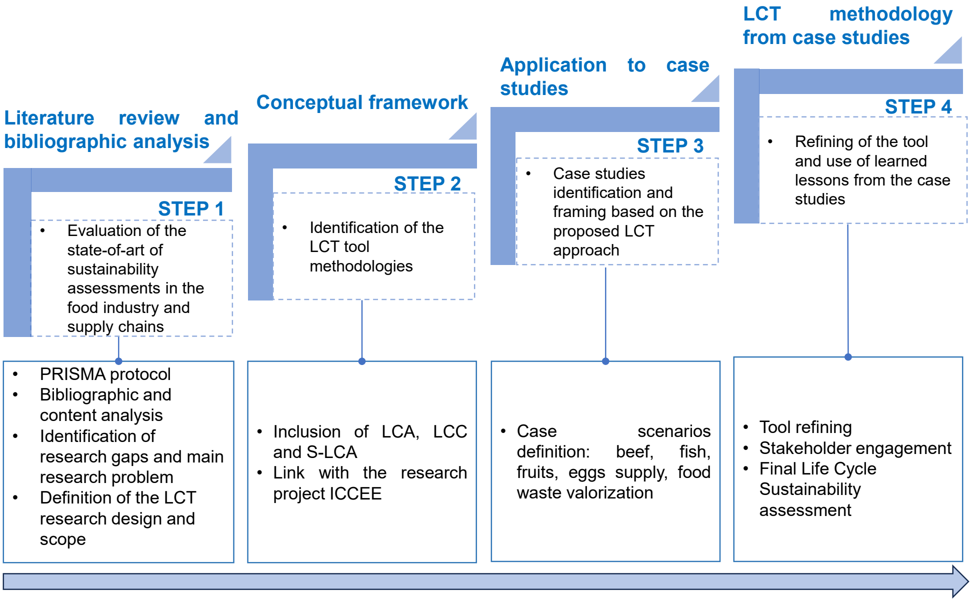


Fig. 1.1. Research framework of the Doctoral Thesis.

The framework consists of four sequential steps.

- Step 1: Literature review and bibliographic analysis.

The research begins with a systematic analysis of existing practices for sustainability assessment in food supply chains, with particular focus on LCT-based methodologies (LCA, LCC, S-LCA). This step identifies methodological gaps and limitations in current approaches, establishing the research problem and defining the scope for methodological development.

- Step 2: Conceptual framework development.

Building on the insights of Step 1, a standardized, quantitative, and multi-dimensional LCT methodology is developed. This framework explicitly integrates environmental, economic, and social dimensions, while adapting to the operational and contextual characteristics of food supply chains. The outcome is a sector-specific conceptual model that operationalizes LCT into an actionable decision-support structure.

- Step 3: Application to case studies.

The proposed methodology is tested through empirical application to selected case studies (beef, fish, and egg cold chains). These represent critical segments of the food industry, chosen for their energy-intensive processes and sustainability challenges. The case studies serve as testing grounds to validate the framework's applicability, identify sustainability hotspots, evaluate trade-offs, and propose targeted interventions for reducing environmental burdens and improving efficiency.

- Step 4: Refinement of the LCT methodology.

Insights gained from the case studies are used to refine and strengthen the proposed methodology. The iterative process enhances robustness, usability, and adaptability, resulting in the development of the life cycle sustainability tool (LCST). This refinement ensures methodological consistency, standardized indicators, and practical relevance for both policymakers and industry practitioners, including SMEs.

Reflecting this framework, the Thesis is structured into chapters covering the literature review, methodology development, case study application, results and discussion, and conclusions with recommendations. Each chapter builds on the previous, demonstrating the interplay between theoretical reasoning and empirical validation.

1.7. Approbation of the research results

1. **Diaz, F**. et al. Effects of Energy Efficiency Measures in the Beef Cold Chain: A Life Cycle-based Study. *Environmental and Climate Technologies,* 25, 343–355 (2021).
2. **Diaz Sanchez, F**. A., Koiro, L., & Romagnoli, F. Energy Efficiency Measures on Cold Supply Chains Problem identification and gaps for the fish sector. Conference Proceedings of the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 1–6, (IEEE, 2021). doi:10.1109/RTUCON53541.2021.9711739.
3. **Diaz, F.**, Koiro, L., & Romagnoli, F. Environmental and economic life cycle evaluation of potential energy efficiency measures on Latvian fish supply chain. *Future Foods,* 6, 100203 (2022).
4. **Diaz, F.** et al. The ICCEE Toolbox. A Holistic Instrument Supporting Energy Efficiency of Cold Food and Beverage Supply Chains. *Environmental and Climate Technologies,* 26, 428–440 (2022).
5. Ruiz, M., & **Diaz, F.** Life Cycle Sustainability Evaluation of Potential Bioenergy Development for Landfills in Colombia. *Environmental and Climate Technologies,* 26, 454–469 (2022).
6. **Diaz, F.**, Pakere, I., & Romagnoli, F. Life Cycle Assessment of Low Temperature District Heating System in Gulbene Region. *Environmental and Climate Technologies,* 24, 285–299 (2020).

Other scientific publications related to the topic, but not included in the Thesis.

- Zlaugotne, B., **Diaz Sanchez, F.** A., Pubule, J., & Blumberga, D. Life Cycle Impact Assessment of Microalgae and Synthetic Astaxanthin Pigments. *Environmental and Climate Technologies,* 27, 233–242 (2023).
- Zlaugotne, B., **Sanchez, F. A. D.**, Pubule, J., & Blumberga, D. Protein Alternatives for Use in Fish Feed – Life Cycle Assessment of Black Soldier Fly, Yellow Mealworm and Soybean Protein. *Environmental and Climate Technologies,* 27, 581–592 (2023).

1.8. Other scientific publications

- **Diaz, F.,** & Cilinskis, E. Use of Multi-Criteria TOPSIS Analysis to Define a Decarbonization Path in Colombia. *Environmental and Climate Technologies,* 23, 110–128 (2019).

- Vamza, I., **Diaz, F.**, Resnais, P., Radziņa, A., & Blumberga, D. Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia. *Environmental and Climate Technologies,* 25, 58–70 (2021).
- Bumbiere, K., **Diaz Sanchez, F. A.**, Pubule, J., & Blumberga, D. Development and Assessment of Carbon Farming Solutions. *Environmental and Climate Technologies,* 26, 898–916 (2022).

1.9. Participation in conferences

- **Diaz, F.,** & Cilinskis, E. Use of Multi-Criteria TOPSIS Analysis to Define a Decarbonization Path in Colombia. *The Conference of Environmental and Climate Technologies CONECT,* 2019. Riga.
- **Diaz Sanchez, F**. A., Koiro, L., & Romagnoli, F. Energy Efficiency Measures on Cold Supply Chains Problem identification and gaps for the fish sector. *IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON),* 2021. Riga.
- Ruiz, M., & **Diaz, F.** Life Cycle Sustainability Evaluation of Potential Bioenergy Development for Landfills in Colombia. *The Conference of Environmental and Climate Technologies CONECT,* 2022. Riga.
- **Diaz, F.** et al. The ICCEE Toolbox. A Holistic Instrument Supporting Energy Efficiency of Cold Food and Beverage Supply Chains. *The final ICCEE conference, towards more energy efficient companies – focus on various industry sectors.* Riga.

1.10. Supervised and co-supervised master's thesis

- Arnis Dzalbs. Analysis and modelling of the cold supply chain of frozen berries: A life cycle-based approach for a Latvian case study. RTU, 2020.
- Lolita Koiro. Energy efficiency measures on cold supply chains: Quantitative approach based on life cycle thinking perspective. RTU, 2021.
- Lelde Matuko. Life cycle assessment of cold supply chains: A case study of a Latvian egg producer. RTU, 2022.

2. LITERATURE REVIEW AND RESEARCH NEED

2.1. Sustainability concept

There is a growing awareness of the planet's finite resources that underscores the need for sustainable systems. This recognition forms the foundation of sustainability, first defined in the 1987 Brundtland Report as "the capacity to fulfill current human requirements while safeguarding the interests of future generations" [2]. Sustainability represents the ultimate goal, while sustainable development is the ongoing process to achieve it. The Brundtland Report introduced intergenerational fairness but left the definition of "needs" ambiguous, raising concerns about the relationship between economic growth and environmental impact. The report focused on human needs without explicitly addressing the natural environment, though it did emphasize its protection.

By 2000, a refined definition of sustainable development emerged, integrating ecological, economic, and social dimensions and promoting social fairness without environmental compromise [3]. From an ecological economics perspective, development is seen as enhancing human well-being alongside sustainable natural resource use [4]. This approach necessitates aligning environmental valuation and policy frameworks to prevent irreversible ecological damage caused by breaking the ecosystems' carrying capacity and resilience thresholds [5].

This new perspective led to the acknowledgment of planetary boundaries [6] and the development of the doughnut economics model, which integrates social and environmental concerns [7] represented by social and ecological boundaries (Fig. 2.1).

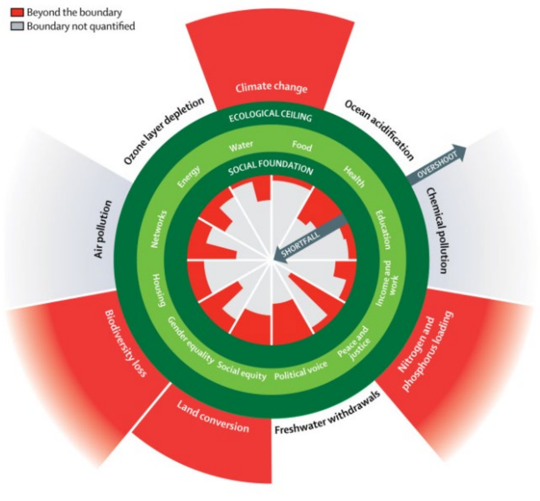


Fig. 2.1. Social shortfalls and environmental overshoot representation [7].

Planetary boundaries, defined in 2009, represent the safe limits within which humanity can operate without disrupting Earth's systems [6]. These boundaries are crucial for understanding environmental sustainability and setting limits for ecosystem stability. Recent research, including work by the Stockholm Resilience Centre, has identified nine critical planetary boundaries, six of which have already been breached, underscoring the need for urgent global environmental action (Fig. 2.2) [9].

In 2015, Bjørn et al. proposed integrating the planetary boundaries framework with LCA to measure "absolute sustainability," ensuring human activities stay within ecological limits [11]. This framework has become vital for scientists and policymakers, offering clear guidelines to address escalating environmental challenges.

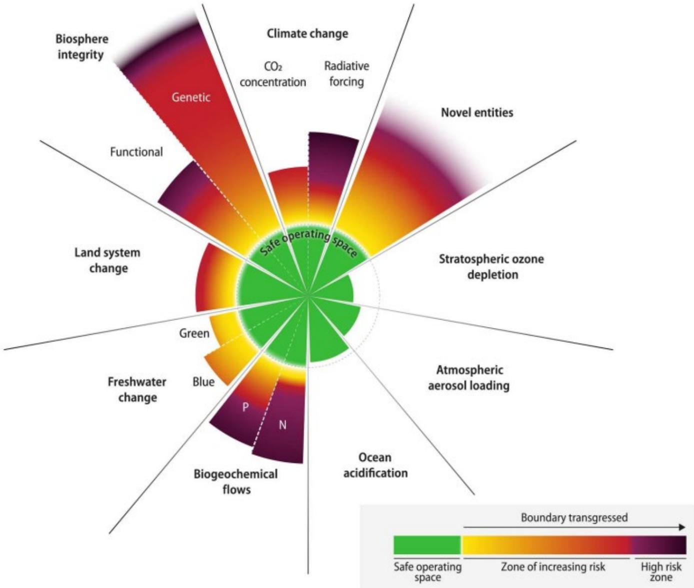


Fig. 2.2. Current status for all nine planetary boundaries [9].

2.2. Sustainability in food supply chains

The food industry's environmental and social impacts are significant as the sector heavily depends on land and resource use, with 70 % of the EU's land utilized for agriculture or forests, significantly influencing rural employment and natural capital preservation. In 2012, the sector generated over €1000 billion, contributing 12.8 % of the EU's manufacturing value and employing more than 4.3 million people [12], [13], [5].

Supply chains in this industry are highly complex, involving multiple stages across various sectors, such as agriculture, aquaculture, packaging, and logistics. Hygiene and refrigeration requirements have increased due to globalization and further escalated energy consumption and resource use [14]. Food losses, driven by safety and perishability challenges, occur at multiple FSC stages, exacerbating societal and environmental issues [15]–[17].

International organizations, such as the FAO and UNEP, focus on reducing food waste through technological advancements in storage and monitoring [18], [19]. Private sector cosmetic standards in food retail also contribute to food waste, particularly in fresh produce, necessitating strategies for waste recovery to meet SDG Target 12.3, which aims to halve food waste by 2030 [20]–[22].

Supply chain management (SCM) has the potential to address both ethical and environmental concerns across the entire supply chain [23]. However, FSC sustainability is complicated by factors like perishability, shifting consumer preferences, and worker conditions. Current research largely uses qualitative methods, such as case studies, to explore sustainability issues [23]–[25], but more research is essential to better understand FSC sustainability, particularly in developing economies where inefficiencies in logistics can amplify food waste.

2.3. Overview of sustainability methods in food supply chains

A systematic literature review on sustainability evaluation in the food industry, specifically within FSC, was conducted using the PRISMA-2020 protocol [26], given increasing attention on the sustainability of food systems among consumers, producers, and policymakers [27].

Sustainability research in FSC has surged in the last years, with fourteen relevant documents identified for 2021 and 2022, marking a 250 % increase over the previous decade. A bibliographic analysis shows that the most cited keywords in the literature are "climate change," "food supply chains," and "supply chain," followed by "life cycle assessment," "sustainability," and "system dynamics." Co-occurrence data shows that "sustainability assessment" frequently appears alongside "food supply chain," "local," "global," "food industry," and "nutrition" between 2016 and 2020.

Figure 2.3 highlights the prominence of combining sustainability assessments in food supply chains with life cycle assessment methodologies. While bibliographic analysis is critical for understanding the core concepts in a research area, a final content analysis was performed on 95 documents, further expanding relevant literature using the AI tool Research Rabbit [28].

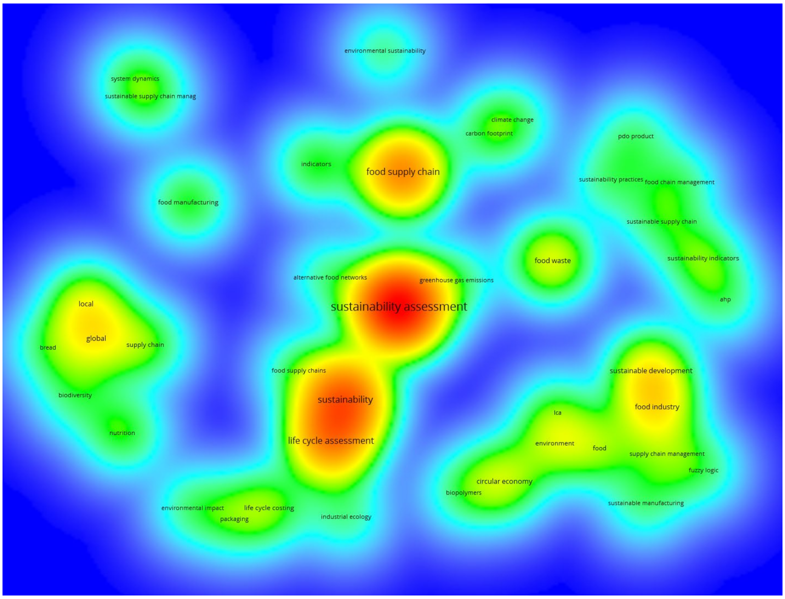


Fig. 2.3. Bibliographic density map.

2.3.1. Content analysis

A content analysis of recent studies has shown the intricate effects of food chain configurations on health and sustainability, emphasizing the interconnectedness of dietary choices and environmental impacts. Researchers advocate for a multidimensional approach to sustainability assessments, incorporating quantitative methods, such as LCA. This is believed to ensure a comprehensive evaluation of broader sustainability impacts, including often overlooked factors like human health [29].

Manufacturing in the food sector has significant environmental, social, and economic impacts. While existing sustainability methods largely focus on environmental factors, as Ahmad and Wong (2019) identified [30]. Their research proposed 57 sustainability indicators, including social, environmental, and economic factors, and employed fuzzy logic and Monte Carlo simulations to manage the inherent uncertainties of sustainability assessments [30]. This approach marked a shift toward more integrated and detailed evaluations of sustainability performance in food manufacturing.

A further content analysis of 95 documents allowed the grouping of methods as presented in Table 2.1.

Table 2.1

List of Methods in FSC Sustainability Assessment

Method	# of papers	Reference
LCA-based methods	26	[31], [29], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55]
System dynamics-based methods	2	[56], [57]
Qualitative evaluations	6	[58], [59], [60], [61], [62], [63]
Fuzzy logic-based-methods	6	[30], [64], [65], [66], [67], [68]
Literature reviews	15	[25], [58], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80]
Multi-criteria decision making (MCDM)	3	[51], [53], [68]
Comparative analysis	2	[29], [81]
Case study-based methods	5	[27], [82], [83], [84], [85]
Indicator-based evaluations	3	[86], [87], [88]
Descriptive/qualitative analysis	1	[89]
Econometric/statistical models	3	[90], [91], [92]
LCC and other life cycle tools	4	[38], [48], [55], [93]
Bibliometric analysis and PRISMA	4	[24], [70], [75], [94]

The content analysis highlights several advantages of LCA, particularly its comprehensive scope in evaluating environmental impacts throughout a whole product's life cycle [31]–[33]. LCA allows for identifying critical areas for sustainability improvements and multiple environmental factors, such as greenhouse gas emissions and resource use, which aids in scenario planning and long-term sustainability strategies. Thus, it is concluded that LCA is the preferred method for evaluating sustainability in food supply chains, as seen in Fig. 2.4.

LCA has limitations, such as its complexity, need for extensive datasets, high costs, and computational demands, which can be challenging for smaller companies. It often focuses primarily on environmental factors, neglecting socio-economic aspects, and is difficult to apply across different regions or industries. Qualitative methods enhance stakeholder engagement and interdisciplinary collaboration but face scalability issues and require context-specific adaptations. Fuzzy logic methods address uncertainties by combining qualitative and quantitative data, though they introduce subjectivity and inconsistencies with standard LCIA methods.

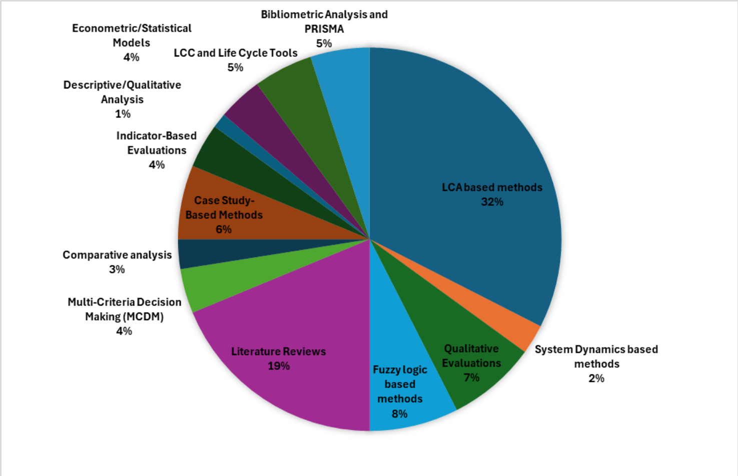


Fig. 2.4. Sustainability assessment methods in FSC.

2.3.2. Industry-level sustainability evaluation methods.

Various sustainability assessment methods, such as those developed by the World Business Council for Sustainable Development, the Global Reporting Initiative, and the OECD, are used to evaluate company performance under the lens of sustainable development [95]–[97]. Indicators and composite metrics are increasingly recognized as vital tools for policy-making and public communication for actionable insights [98]–[102]. These assessments guide decision-makers in understanding integrated nature-society systems and promoting sustainable practices [103].

Different industries approach sustainability in varied ways. For instance, the chemical industry follows the Together for Sustainability (TfS) framework, which only evaluates GHG emissions [104]. In contrast, the Environmental, Social, and Governance (ESG) framework has become widespread since the early 2000s, guiding companies to manage sustainability risks and opportunities across a range of concerns, including climate change and social justice [105], [106]. However, ESG reporting primarily supports financial sustainability decisions and does not directly reflect overall sustainability performance because it lacks a context-based approach [107], [108].

New regulations, such as the EU's Corporate Sustainability Reporting Directive (CSRD), enforce standardized ESG and sustainability disclosures, aligning with broader SDG goals

[109], [110]. Other sectors, like construction, have adopted EPDs to provide transparent data on products' life cycle environmental impacts, but ignore financial and social dimensions [111].

LCA tools like SimaPro and GaBi face limitations in real-time adjustments of the life cycle inventory (LCI) and complex system boundaries, making them less practical for SMEs [110]. To encourage broader adoption of sustainability assessment tools, user-friendly, affordable, and secure LCA software is necessary, allowing even professionals with basic LCA knowledge to generate accurate results.

2.3.3. Food supply chain considerations

Global population growth and trade liberalization have driven FSC globalization, leading to longer distances from production to consumption, higher resource use, and more emissions [15], [29]. Efforts like carbon labeling and 'carbon miles' aim to raise consumer awareness, but these initiatives only partially address the overall environmental load [112], [113].

To mitigate these effects, more sustainable FSCs are essential, as food loss has both societal and environmental costs. The FAO, WFP, and UNEP are working to reduce food loss, which is critical for achieving the Zero Hunger Challenge [21], [114], and new technologies, including smart monitoring and temperature control, are key to reducing food loss while maintaining quality [115], [116].

Consumer demand for high-quality and environmentally sound products also influences FSC management [117]. But maintaining food quality, especially for perishable items, requires carefully balancing safety, efficiency, and profitability. Food Waste is defined by the FAO as food discarded due to negligence, with increasing attention on its environmental and social impacts [121]–[123].

FW occurs at various stages, with 25–40 % of waste at supermarkets often exacerbated by retailers' rejection of edible food based on appearance [128], [130]. Globally, 30 % of food production is lost, with the FAO reporting 1.3 billion tons wasted annually, representing a 48 % loss in calories [135], [136].

Addressing food loss is vital for global sustainability, human health, and resource conservation [137]. While power production receives much attention in climate change discussions, the food system is overlooked despite accounting for 26 % of global GHG emissions. The main contributors are livestock, fisheries, crop production, and land use [138]. Reducing food waste in supply chains is critical, as FSC activities represent 18 % of the food industry's emissions [139].

2.3.4. Additional Sustainability Considerations

FSC’s environmental impacts are both direct, stemming from the use of resources like raw materials and energy, and indirect, such as the effects of food waste. Today’s refrigerants used in cold storage and transport, such as hydrochlorofluorocarbons (HCFCs), which replaced CFCs, have a lower ODP, but come at a high global warming potential (GWP), contributing to climate change and biodiversity loss [140], [141].

FW also has substantial environmental consequences, accounting for 3.3 Gt of CO_2 equivalent annually, making it the third-largest emitter globally, after the USA and China, from a country-size perspective [121]. FW results in the destruction of vast amounts of water and land, with close to 1.4 billion hectares – nearly a third of the world's agricultural land.

FSCs face challenges due to regulatory and environmental pressures, such as traceability and packaging standards, which vary across regions [142], [143]. Waste reduction and packaging reuse are vital for improving sustainability in FSCs, and these efforts also impact social responsibility initiatives [144]–[146].

Sustainability in FSCs also requires social indicators, like human rights and occupational safety, which are hard to quantify [147]–[153]. Although natural resource management, transport, and storage are crucial for sustainable development in the EU, more research is needed on FSC sustainability, particularly in quantitative environmental and social impact assessments [154], [70].

2.3.5. Research gaps

In today's sustainability-driven context, effective tools are needed to assess and guide sustainable practices. Traditional environmental assessments often focus on limited or short-term impacts, missing the broader complexity of sustainability. Life cycle thinking offers a holistic approach, assessing impacts across the full life cycle of a product or service. Unlike traditional "cradle-to-grave" methods, LCT uses a "cradle-to-cradle" lens, covering all stages from raw material extraction to end-of-life, and identifying opportunities for circularity and innovation.

Despite its strengths, LCT is not widely implemented through accessible, industry-specific tools. Existing tools often lack comprehensive data, adaptability, or usability, particularly for SMEs, creating a gap between academic models and practical applications. There is a clear opportunity to develop a robust, user-friendly decision-support tool based on LCT that can identify sustainability hotspots, support targeted actions, and assess trade-offs across environmental, social, and economic dimensions.

The literature review identifies key gaps that define the research problem and objectives.

1. Bridging theory and practice. LCT is a well-established concept, but it lacks practical tools for real-world decision-making.
2. Integration of multi-dimensional sustainability. Most tools focus on environmental impacts, with limited inclusion of social and economic aspects aligned with SDGs, CSRD, and ESG frameworks.
3. Industry-specific contextualization. Generic tools don't address unique challenges of food supply chains such as perishability, refrigeration needs, and high food waste, highlighting the need for tailored approaches.
4. Operationalization of planetary boundaries and absolute sustainability. These concepts are acknowledged in theory but rarely applied at the product or process level, limiting their use in aligning supply chains with global sustainability limits.

These gaps highlight the need for a comprehensive, practical, sector-specific LCT-based methodology that supports sustainability assessment and improvement across food supply chains.

3. METHODOLOGY

This Thesis proposes a novel approach for the sustainability assessment of FSCs based on LCT methodologies. The aim is to improve existing approaches by providing a broader perspective on sustainability issues and supporting collaboration among different actors within the FSC for a more consistent evaluation. The research follows a quantitative methodology to test the central hypothesis, structured into four main steps, from defining the research problem to developing an LCST prototype and final documentation, including this Thesis. A visual representation of the methodology is provided in Fig. 3.1.

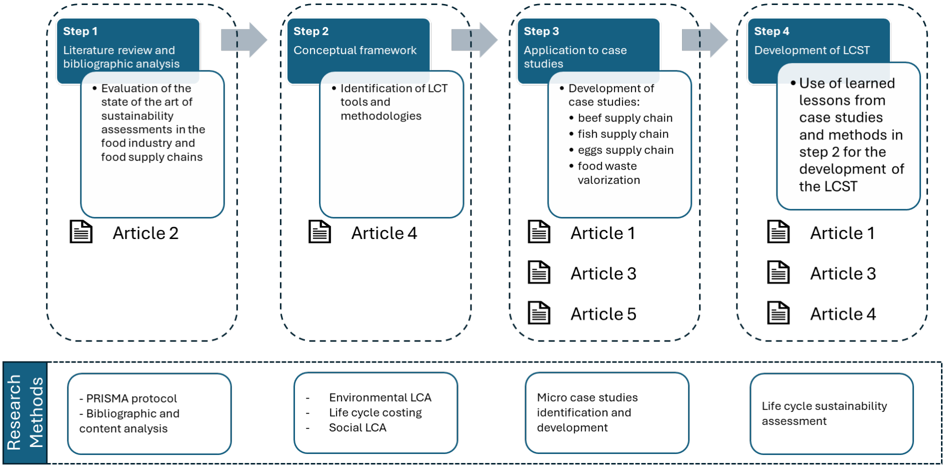


Fig. 3.1. Research framework and methods of the Doctoral Thesis.

Following an initial assessment of sustainability methodologies in the food industry, the research problem was defined alongside the development of the ICCEE project. A literature review was then conducted to examine the current state of sustainability in the sector, leading to the formulation of the research scope, hypothesis, and main objectives. While these stages are presented sequentially, they were not strictly linear, as revisiting objectives and scope is common in quantitative research [156].

During this phase, various food supply chains were analyzed to identify key sustainability hotspots. This informed the development of a dynamic tool designed to capture supply chain complexity and assess sustainability across multiple dimensions.

The final phases focused on analyzing case study results, refining the life cycle sustainability tool (LCST), and validating its functionality. The outcomes supported the creation of a final tool version capable of delivering the intended results.

This study follows a top-down research approach, starting from broad concepts and progressively focusing on specific elements. Key characteristics of this method include:

• beginning with overarching theories or frameworks and narrowing down to specific case studies;

• use of established theories to inform data collection and analysis;

• a structured, linear methodology moving from general to specific;

• emphasis on macro-level trends and principles in early stages;

• early findings guide the direction of more detailed subsequent research.

This approach is common in policy, economic, and social research, and was applied here to move from general sustainability frameworks toward a targeted solution for food supply chains.

3.1. Research methods

The research methods are described in the following sections.

3.1.1. PRISMA Protocol

This Thesis applied the PRISMA methodology to guide the bibliographic and content analysis presented in the Literature Review (Fig. 3.2). The PRISMA-P protocol supports transparency, consistency, and completeness in systematic reviews by preventing arbitrary decisions and promoting clear documentation. It includes a 17-item checklist for structuring review protocols [28]. Widely accepted in the research community, PRISMA assists authors, reviewers, and funders in developing rigorous reviews. Recent updates in PRISMA 2020 reflect advancements in review methods and incorporate user feedback to improve its effectiveness [157], [158], [26].

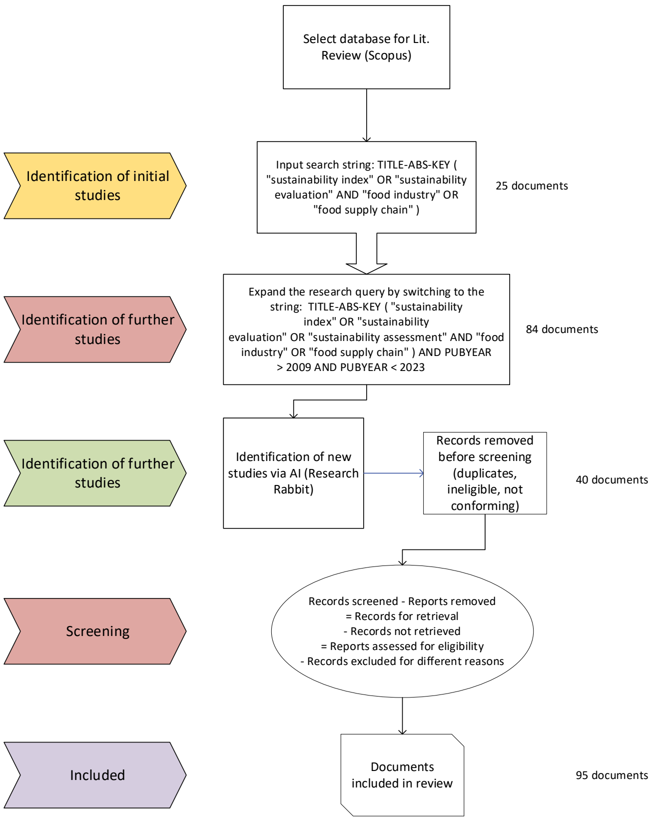


Fig. 3.2. Systematic Literature review scheme following the PRISMA protocol.

3.1.2. Environmental LCA

Environmental LCA is essential for evaluating ecological impacts across the full life cycle of products and processes. Unlike carbon footprint, which focuses on a single impact, LCA covers multiple categories such as global warming, resource depletion, and ozone depletion [159], [160], [66]. The methodology follows ISO standards 14040:2006 and 14044:2006, comprising four stages: goal and scope definition, LCI, LCIA, and interpretation. This structure supports informed sustainability decision-making [161], [162].

LCA now addresses broader concerns like climate change, biodiversity loss, and pollution, extending its application from product-level to system-wide assessments vital for decarbonization and circular economy strategies [163], [164]. Recent developments highlight the integration of other assessment methods into LCA, though greater standardization is needed to ensure consistency and comparability [37], [164]. Connecting LCIA results to planetary boundaries is increasingly important for evaluating sustainability in the agriculture and food sectors [41], [165], [166]. Arias et al. demonstrated this by linking planetary boundaries to LCA in the wood-based bioadhesive sector, underscoring the importance of such integration [165].

Ensuring sustainable practices within Earth's safe and just limits requires stakeholder collaboration and robust, transparent methods that account for assumptions and uncertainties [167], [168].

In this research, the environmental LCA followed the ISO 14040 and 14044 frameworks across all case studies, implemented using the SimaPro software with a predefined LCIA method. Although each case was conducted independently, all adhered to the same methodological structure. The LCST focuses on evaluating environmental impacts up to the product use phase. The specific LCIA method used in the tool is detailed in Subsection 5.1.1.

3.1.3. Life cycle costing

LCC accounts for all costs across a product or project life cycle, including suppliers, producers, consumers, and end-of-life (EoL) actors. Evolving from project appraisal, LCC now supports environmental impact assessment, sustainability analysis, LCA, and societal assessments. Traditional cost methods may omit EoL costs or environmental considerations, so LCC should cover the full life cycle and, as needed, extend system boundaries to environmental and social factors [169].

Figure 3.3 presents three LCC approaches: conventional (C-LCC), environmental (E-LCC), and societal (S-LCC). C-LCC focuses on costs to the producer or user, often excluding EoL and other stages, which limits compatibility with LCA [170]. E-LCC aligns system boundaries and product models with LCA, includes supplier-chain costs typically omitted by C-LCC, and serves as a complementary component within sustainability assessments rather than a standalone method [163], [171], [172].

E-LCC, combined with LCA, is used to compare life cycle costs, identify direct and indirect cost drivers, estimate improvements from product modifications, and reveal win-win options. It follows goal and scope definition, data collection, interpretation, hotspot detection, and sensitivity analysis, with quantitative and qualitative interpretations that include investment appraisal tools and nonmonetary factors such as market type and sales volume [170], [171]. Like LCA, E-LCC uses direct cost data per unit process. Indirect costs in complex settings may require activity-based costing. Costs for materials, energy, and operations are aligned with LCA reference flows [170], [173], [174].

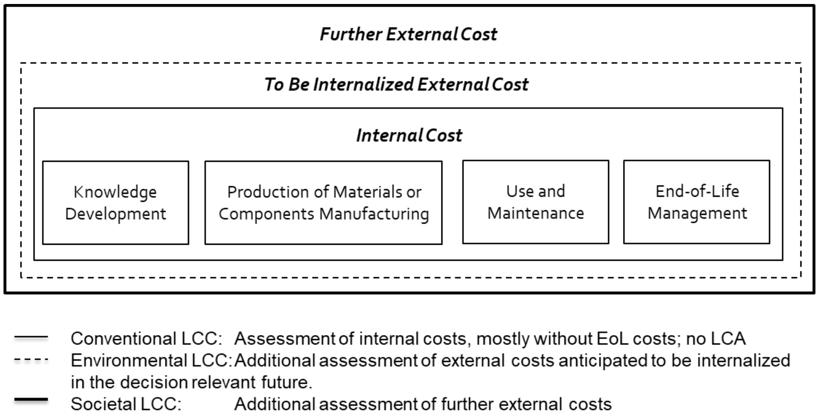


Fig. 3.3. System boundaries for different LCC approaches [170].

S-LCC extends beyond E-LCC to include costs borne by all social actors and externalities such as public health and environmental impacts, which is relevant for corporate social responsibility and public decision-making [169], [171], [172], [175]. LCC modelling follows economic cost categories, life cycle stages, and activities, allocating indirect costs with physical or financial parameters. In FW studies, stakeholders differentiate expenses along the supply chain to assess prevention and management options aimed at reducing FW and improving efficiency [169], [170].

In this research, LCC complements LCA to evaluate the economic sustainability of food supply chains, although integration with LCA remains methodologically nonstandard and multi-dimensional, particularly for food products and FW management [169], [176]. The preferred approach is E-LCC, which covers costs borne by life cycle actors and externalities expected to be internalized in the decision-relevant future, consistent with [170].

Some important aspects for implementing E-LCC in this study are:

- Cut-off criteria: use an environmental cut-off. Exclude cash flows for processes such as labor and capital. Include only cash flows linked to material flows such as energy, fuels, and materials.
- Cost modeling by activity or stage, focusing on the material flows considered. This yields a cold chain cost per product within E-LCC.
- Externalities such as investment costs and the monetary valuation of environmental impacts, using a standard economic conversion factor, can be included under E-LCC.
- A steady-state model is required, since most LCA applications lack temporal specification and assume constant technologies [177].

- For future scenarios that include energy efficiency investments, use socio-economic indicators such as cost/benefit ratio or net profit.
- E-LCC's main advantage over conventional LCC is its consistency for sustainability assessments, since some external costs are internalized. It supports internal decision-making and external communication, similar to LCA.
- Assessed cost categories: development, materials, energy, transport, and emissions.

Consistent with the LCA system boundaries, the E-LCC goal in the study cases and tool development is to identify the economic impact of energy and material flows in food supply chains. The scope supports decision-making by comparing scenarios with and without energy efficiency measures. As shown in Fig. 3.4, the system boundaries begin after the final product is stored in the manufacturer's warehouse. To enable single-actor evaluation, C-LCC is also applied, with boundaries focused on the processing stage, as in Fig. 3.4.

For tool users, the aim is to simplify LCC evaluation and reveal the benefits of flow changes due to energy efficiency measures. With the environmental cut-off, CAPEX and OPEX calculations are avoided by assessing only material and energy flows per functional unit. Scenario impacts are reflected in those flows, including energy, fuels, refrigerants, and electricity.

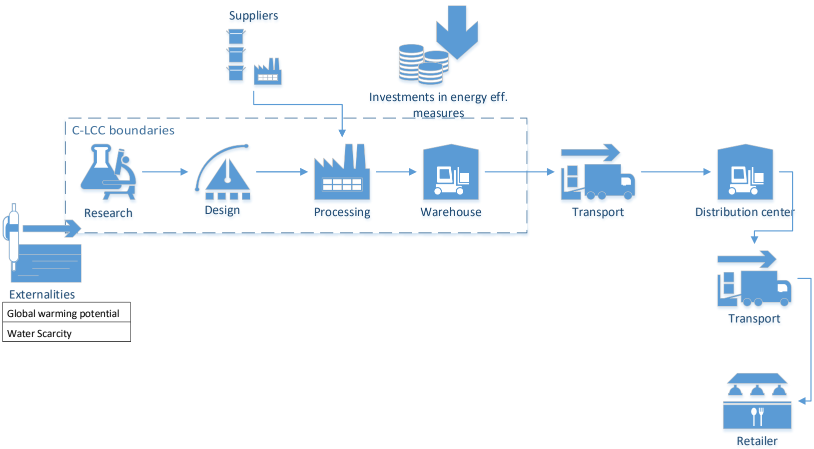


Fig. 3.4. Evaluated C-LCC system boundaries.

3.1.4. Social LCA and its challenges

The social pillar prioritizes basic needs and fair access to sustainable development benefits. Persistent issues include inequality, human rights violations, malnutrition, limited access to clean water, disease, illiteracy, refugee crises, and gender inequality. The SDGs and ISO 26000 address these challenges [20]. Technological change and population growth intensify environmental and social pressures, risking growth that depends on material and energy use. A reduction, reuse, and sharing paradigm is needed to build a bioeconomy that decouples well-being from environmental degradation, supported by collaboration among researchers, industry, consumers, and policymakers [178].

Social impact assessment captures qualitative aspects of sustainability and diverse stakeholder views. Social life cycle assessment (S-LCA), as an extension of LCA within LCT, evaluates social impacts of products and services [179]–[182]. UNEP, SETAC, and the Life Cycle Initiative provide S-LCA guidelines that classify six stakeholder groups, define impact subcategories, and specify indicators using inventory data. Current practice follows goal and scope, S-LCI, S-LCIA, and interpretation, identifying stakeholder social subjects and key decision issues [183]–[185].

Communicating social implications supports responsible consumption and production. Uses vary across businesses, consumers, and NGOs. In firms, S-LCA informs socially responsible practices and competitive strategy; approaches include innovation, choice manipulation, and choice editing, with community benefits such as market creation and talent retention [186], [187]. NGOs raise awareness of harms such as child labor and unsafe conditions, while multi-actor collaboration has shaped international responsibility frameworks [42], [180], [188].

Because impact pathway standards in S-LCA are limited, the reference scale is often used in research, but it is semi-quantitative and does not follow the input-output transformation used in LCIA for LCA or LCC [183]. Implementing the UNEP reference scale requires qualitative tools such as interviews and context-specific analysis, which complicates integration into the LCST. This project, therefore, adopts an approach aligned with the S-LCA methodology (Subsection 5.1.3) within the LCST, allowing the practitioner to include willingness to pay for externalities such as global warming potential and, by agreement among partners, human health effects or ecosystem damages. This choice affects life cycle costs and the environmental assessment, with safeguards to avoid double-counting. The approach reflects the social cost concept, including the social cost of carbon dioxide, which monetizes damages per additional metric ton of CO_2 and has risen with improved models, influencing climate policy appraisals [189].

3.1.5. Life cycle sustainability assessment

An LCT approach was implemented in parallel with the ICCEE project, which supports energy efficiency in food and beverage cold chains through supply chain energy assessments. Although ICCEE focuses on cold chains in the food sector [190], this Thesis approach applies to any food supply chain, refrigerated or not. The research adopts a chain-level perspective to expand opportunities for energy efficiency.

The work integrates food and beverage supply chain characteristics into an analytical decision-support tool with tailored energy performance analyses across stages such as raw material preparation, logistics and warehousing, production and processing, and packaging. To aid updates of energy efficiency measures and decision-making on energy-saving potential, a dedicated cold supply chain energy efficiency tool was designed and delivered.

Environmental LCA, LCC, and S-LCA were applied simultaneously and consistently across case scenarios, following a standardized procedure. Detailed case descriptions are provided in Section 4.1. Anticipated LCT benefits include:

- supporting choices that account for environmental, economic, and social impacts across the life cycle;
- allocating responsibilities across design, production, and consumption;
- enabling long-term decisions across air, water, and land;
- guiding eco-design toward cleaner products and processes;
- enhancing H&S, risk, and quality management;
- supporting governmental initiatives that protect the environment and society;
- informing consumers on purchasing, transport, and energy choices, encouraging engagement with industry and government.

LCT clarifies trade-offs and synergies among life cycle stages, enabling process optimization for near-term and long-term sustainability. A comprehensive view prevents shifting burdens and embeds environmental factors in decision-making.

LCA underpins ecodesign and manufacturing, with recent integrations covering production equipment, technical services, and energy supply. LCSA helps identify sustainability hotspots in goods and processes [191]–[193]. LCA's versatility spans sectors [194], including pharmaceuticals, where it guides lower-impact chemical processes [195], and construction, where it informs materials, waste management, and infrastructure impacts [196]–[200].

Building on Section 2.5 ("Research gaps") and tests in [96], this work proposes a sustainability assessment method based on LCT tools, aligned with the Thesis hypothesis and objectives. The focus extends beyond carbon to ecological, social, and economic pillars, with attention to unintended consequences that often burden poorer nations [201], [202]. Holistic actions yield co-benefits, such as reducing overconsumption, supporting local businesses, and strengthening education [61], [203]–[205]. Ecosystem regeneration practices enhance biodiversity and carbon sequestration [206], [207]. A holistic perspective is essential to align human activity with the ecosphere [208].

Although LCSA lacks a unified framework, Fig. 3.5 outlines the main impact indicators. The mind map draws on common environmental midpoint categories from LCIA, LCC indicators [170], and S-LCA indicators from UN guidelines [183], [209]. LCSA supports transitions in the energy sector by clarifying challenges, methods, and indicators [210]. Food LCA spans upstream and downstream processes [17], with growing use of LCT to cut environmental and social impacts and a rise in n-LCA that integrates nutrition into assessment [211]. Given the agri-food chain's complexity, harmonized measurement and full life cycle perspectives are needed to apply circular economy principles, and lifecycle-based dashboards have been proposed for cross-sector testing [212], [213]. Environmental assessment in agri-food has expanded markedly since the 1970s, reflecting the evolution of LCA in this sector [214].

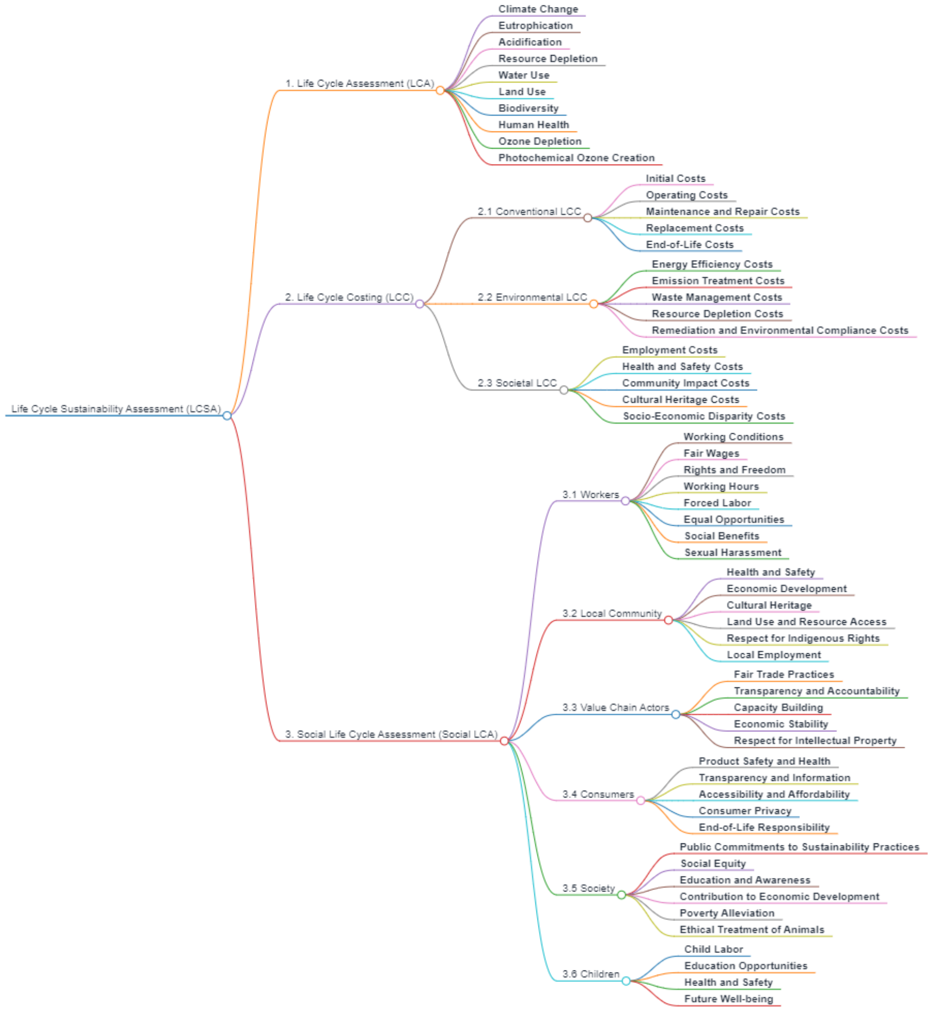


Fig. 3.5. Life cycle sustainability assessment KPIs.

Adoption of life cycle thinking across industries reflects growing recognition of the need for comprehensive environmental impact evaluation. LCT supports innovation and informed decisions aligned with global sustainability goals and should continue to evolve and be applied across sectors. Content analysis in the literature review indicates the need for a more comprehensive, iterative LCSA framework. The proposed framework accommodates different research objectives across topics and activities and is presented in Fig. 3.6.

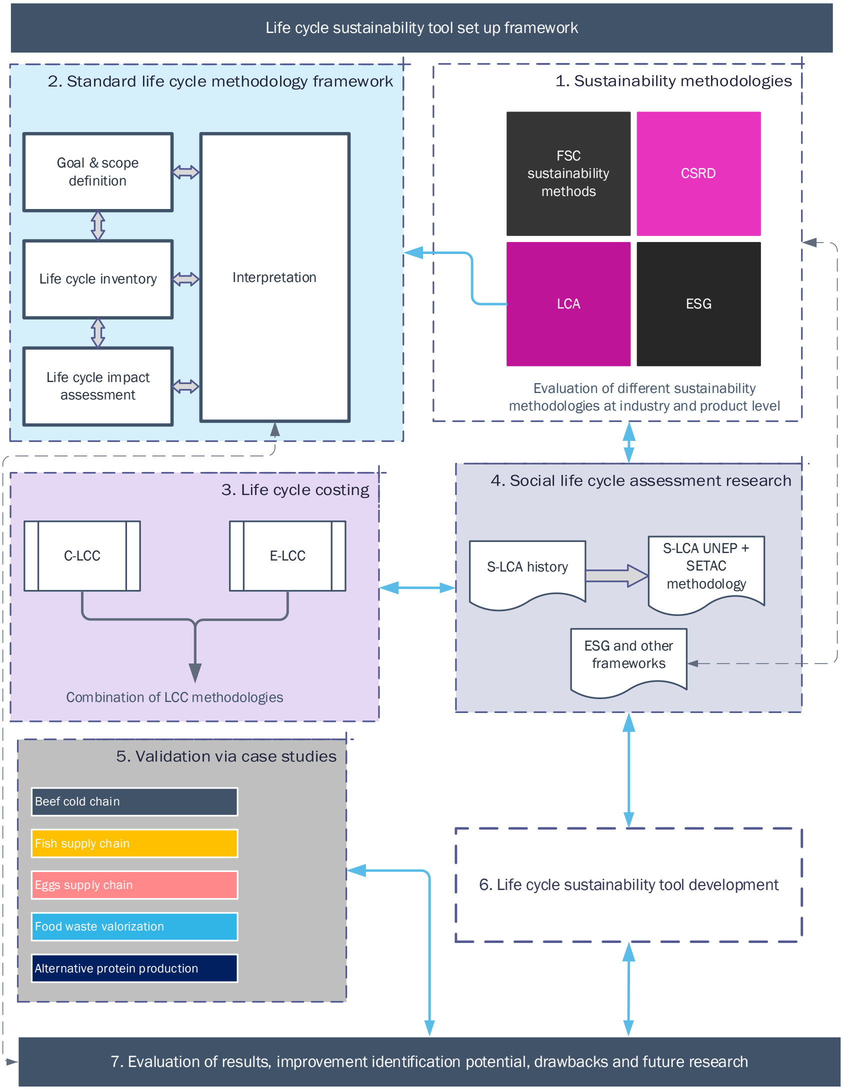


Fig. 3.6. Integrated research methodology into a life cycle sustainability framework.

4. RESULTS AND DISCUSSION

The methodological approach was tested in several micro case studies, thanks to the development of the ICCEE project [215]. In each developed case, a thorough analysis of the supply chain energy performance (and the parameters influencing it) was needed to understand where the energy consumption comes from and how to reduce it at the different stages of the food and beverage supply chain.

It is worth noticing that the impact assessment methods for LCA or LCC types were not always the same in all case studies. This was done to test different methods and evaluate the advantages and shortcomings of each one of them. The learnings from this process were later considered for the definition of the LCST framework implemented in this research.

4.1. Case studies description and main results

Four case scenarios were developed and tested during the research and development of a sustainability framework, some represented in published scientific papers and others during the supervision of the master's thesis. The following sections present a brief description of the goal and scope, functional unit, system boundaries, and central aspects of the life cycle inventory. For a full description of the methodology and results of each case scenario, please refer to the annexed papers.

4.1.1. Beef supply chain

This study evaluates the environmental impacts of a regional and local beef cold chain within a European context. The beef cold chain is complex, involving various stages such as slaughtering, processing, storage, and transportation across different geographical areas. Four scenarios, including a baseline, were analyzed to compare their performance (detailed in Article 1):

- 1) baseline scenario;
- 2) energy recovery scenario: converting biowaste into biogas with cogeneration of heat and power (CHP) (EEM-1);
- 3) renewable energy use: integrating photovoltaic solar energy (EEM-2);
- 4) efficient compressor replacement (EEM-3).

The study models these supply chains without including the end consumer stage due to its variability. Both the regional and local beef cold chains, including post-processing storage, transportation from the farm to the slaughterhouse, from the slaughterhouse to processing, processing to a central distributor, and then to wholesale and retail (see Fig. 4.1).

In this study, the functional unit (FU) is defined as 1 kg of beef delivered to the wholesaler or retailer. All reported values, including energy consumption, packaging, waste, water usage, and transportation, are normalized to 1 kg of product.

A distinction is made between regional and local supply chains. The regional cold chain begins with breeding in Villareal, Spain, followed by slaughter in Tarragona (200 km transport distance), and meat processing and storage in Lleida (100 km distance). From Lleida, the beef is transported 1240 km to Florence, Italy, for distribution, with a final 20 km transport to supermarkets within Florence.

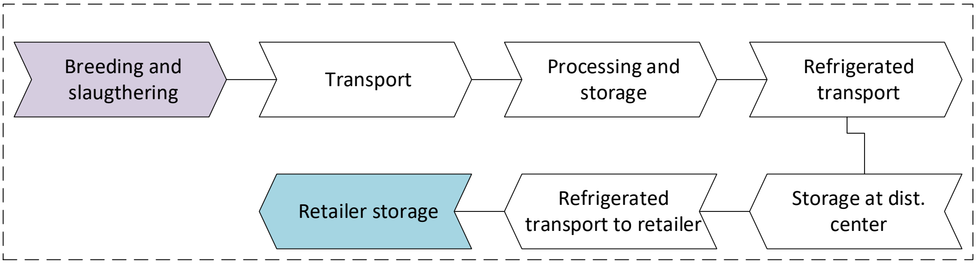


Fig. 4.1. Beef supply chain.

The local cold chain begins with breeding in Tolmezzo, Italy, followed by slaughter in Castelfranco Veneto (200 km transport distance), and processing in Verona (100 km distance). From Verona, the beef is transported 500 km to Rome's distribution center, with a final 20 km transport to local supermarkets. Data for this study were obtained from two Italian processing companies involved in cutting, freezing, and packaging beef. The LCI details are provided in Table 4.1.

Table 4.1

LCI for the Processing Stage in the Beef Supply Chain

Material	Regional	Local
Output - frozen meat (beef), kg	**1.0**	**1.0**
Output - meat organic waste, kg	**0.66**	**0.66**
Input - raw meat, kg	1.66	1.66
Thermal energy, MJ	2.391	2.391
Electricity, kWh	0.14742	0.12346
Tap water, kg	0.013	0.0042
Packaging material - polyethylene, low density, granulate, kg	0.000056	0.000066
Packaging film, low density polyethylene, kg	0.0046	0.00583
Occupation industrial area, m²	0.000221833	0.00031

Table 4.2

LCI for Storage at the Distribution Center in the Beef Supply Chain

Material	Regional	Local
Output – frozen meat, kg	**1.0**	**1.0**
Input – frozen meat, kg	1.0	1.0
Electricity, kWh	0.01957	0.01957
Tap water, kg	0.034463	0.0282
Occupation industrial area, m²	0.000002712	0.000002712

Table 4.3

LCI for Storage at the Retailer for the Beef Supply Chain

Material	Regional	Local
Output – frozen meat (beef), kg	1.0	1.0
Input – frozen meat, kg	1.0	1.0
Electricity, kWh	0.04	0.04
Occupation industrial area, m^2	0.000042462	0.000042462

Main findings. A total environmental impact of 140 mPt was found for the regional supply chain scenario. The most relevant stages are transported from the processing facility to the distribution center, followed by the processing phase.

When looking at the areas of concern, the environmental burden is mainly on climate change and resource consumption and slightly less on human health, leaving the ecosystem quality only mildly affected. The results of the local beef supply chain are similar since most activities require similar energy consumption and are performed very similarly. Nevertheless, the shorter distance for transport activities, especially for reaching the distribution center after processing, makes this supply chain less environmentally intense, with a total score of 90 mPt (see Fig. 4.2).

Additionally, the study revealed that EEM-1 provided environmental benefits in all areas of concern, while EEM-2 and EEM-3 showed minimal improvements compared to the baseline. EEM-1 could also offer environmental credits by reducing electricity consumption from fossil fuels and hydropower land use [218]. The shorter transport distances in the local supply chain, combined with EEM-1, resulted in a negative environmental score, indicating an overall benefit.

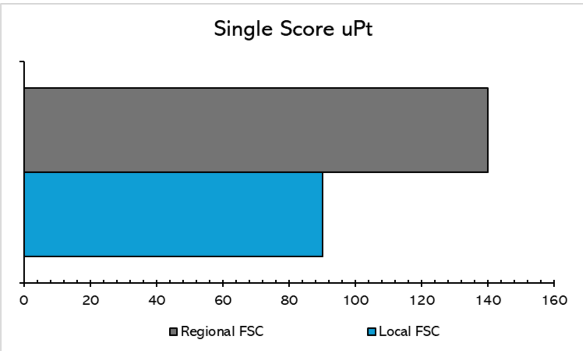


Fig. 4.2. Weighted results across different EEMs in the local supply chain.

The case study also conducted an LCC to compare the economic performance of the different EEM alternatives. Sensitivity analysis showed that fluctuations in beef market prices could impact the internal rate of return or profit index, assuming constant production capacity. The net present value (NPV) analysis indicated that EEM-1 was the most economically favorable option. Further details can be found in Article 1.

4.1.2. Fish supply chain

This case study focused on the Baltic region, specifically Latvia, which receives EU financial support to implement the Common Fisheries Policy (CFP) [217], [218]. In 2019, Latvia's fish production reached 110,200 tons of live weight, with the aquaculture sub-sector contributing 626.4 tons of fish and crustaceans [219], [220]. Despite the fish sector's importance in the Latvian economy, its environmental impact remains unassessed.

A baseline scenario was developed for chilled Latvian cod, and two specific energy efficiency measures were explored along the cold supply chain. The business-as-usual scenario assumes that cod is exported to other countries within the European Economic Area. Figure 4.3 presents the system boundaries for this case scenario, which were defined based on LCA studies of fish products in the European context [221]–[223].

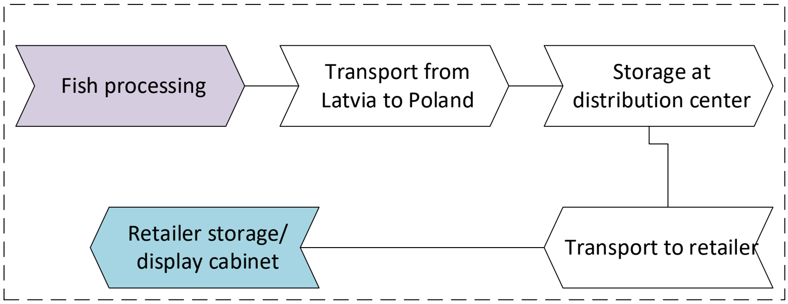


Fig. 4.3. Fish supply chain system boundaries.

It was assumed that the fishing vessels would dock at the port of Ventspils, a key location in Latvia known for its traditional fishing activities. All processing required to produce filleted codfish is assumed to occur in Ventspils, with no downstream waste occurring.

The environmental conditions for transporting the fish are at –2 °C for superchilled cooling technology and +2 °C for chilled conditions. Diesel consumption for the auxiliary unit is estimated at 3.68 kg/h. The refrigerant used is R-134a, with an annual precharge of 6.5 kg and a leakage rate of 10 % per year. A summary of the collected LCI is presented in detail in Article 3.

A C-LCC approach was used to compare two EEMs against the baseline scenario. The first scenario (EEM-1) involves anaerobic digestion (AD) with a CHP plant, while the second (EEM-2) models a photovoltaic plant at the retailer facility, supplying 20 % of its electricity consumption.

Main results: The environmental profile of the model was evaluated using the IMPACT 2002+ method, which provides results at both mid-point as recommended by ISO 14044 (see Table 4.4) and end-point categories [163].

Figure 4.4 presents the results at the end-point category level. The identified hotspots are the storage at the supermarket/retailer, processing stage, and transport under superchilled conditions, especially in the areas of the use of resources, human health, and climate change.

Table 4.4

Mid-Point Category Results for the Baseline Scenario

Impact category	Unit	Processing	Transport to distr. center	Distribution center	Transport to retailer	Retailer
Carcinogens	kg C_2H_3Cl eq	4.8E-03	8.6E-04	1.4E-06	1.8E-04	1.8E-03
Non-carcinogens	kg C_2H_3Cl eq	3.2E-03	3.1E-03	1.7E-06	6.4E-04	2.3E-03
Respiratory inorganics	kg PM2.5 eq	1.5E-04	1.4E-04	1.3E-07	2.9E-05	1.8E-04
Ionizing radiation	Bq C-14 eq	0.91	1.17	0.00	0.24	2.66
Ozone layer depletion	kg CFC-11 eq	9.9E-09	2.7E-08	2.4E-11	5.6E-09	3.3E-08
Respiratory organics	kg C_2H_4 eq	1.1E-04	7.3E-05	4.2E-08	1.5E-05	5.7E-05
Aquatic ecotoxicity	kg TEG water	14.33	15.75	0.02	3.23	23.41
Terrestrial ecotoxicity	kg TEG soil	3.86	11.54	0.00	2.36	5.51
Terrestrial acid/nutri	kg SO_2 eq	2.3E-03	3.1E-03	2.9E-06	6.4E-04	4.0E-03
Land occupation	m^2org.arable	1.6E-02	1.7E-02	3.5E-05	3.4E-03	4.8E-02
Aquatic acidification	kg SO_2 eq	6.8E-04	5.8E-04	8.4E-07	1.2E-04	1.1E-03
Aquatic eutrophication	kg PO_4 P-lim	2.1E-05	1.4E-05	1.2E-08	2.8E-06	1.7E-05
Global warming	kg CO_2 eq	0.17	0.15	0.00	0.03	0.21
Non-renewable energy	MJ primary	3.90	2.38	0.00	0.49	3.60
Mineral extraction	MJ surplus	4.7E-03	1.6E-03	1.1E-06	3.3E-04	1.4E-03

The processes with the leading environmental burden are the electricity consumption at the retailer, the vehicle utilization for transport to the distribution center, the slaughterhouse waste treatment, and the use of the chosen packaging material for the fish fillets at the processing stage (see Fig. 4.4). Compared with other stages, the low impact delivered by the transport to the retailer (also known as food miles) aligns with the discussion summarized in the study by Coley et al., 2013 [224].

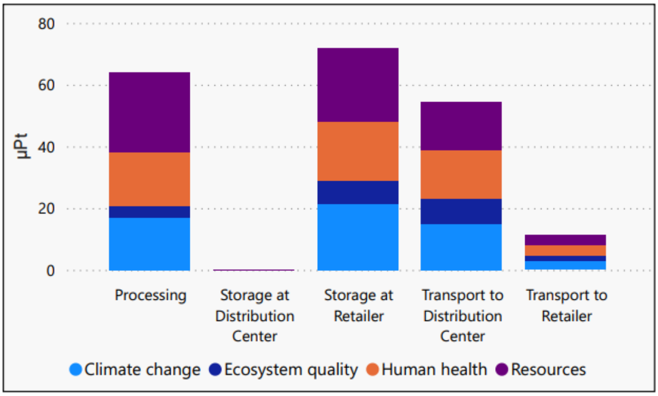


Fig. 4.4. Single score results for the baseline scenario.

The considered EEMs in this case study are the following:

- energy recovery from biowaste (EEM-1);
- electricity production from a PV system (EEM-2).

Figure 4.5 presents a scenario comparison at single score results, with the baseline scenario having the highest impact. The EEM-1 has the highest potential to reduce the total environmental impact delivered by the fish supply chain in the context evaluated. While the EEM-2 would result in a total saving of µPt (6.8 %), the EEM-1 could potentially reduce the impacts by 69.2 µPt (34.3 %) in this FSC.

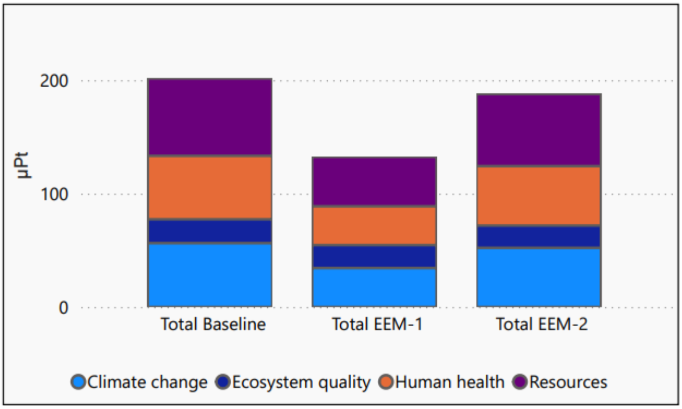


Fig. 4.5. Single score comparison results for the three supply chain scenarios.

A sensitivity analysis was performed to determine the impact of independent input parameters on the single score result. The two independent variables are the transport distance from the processing plant to the central warehouse and the energy consumption at the processor unit process. These variables were chosen considering the impact they both deliver to the overall baseline scenario.

The scenarios considered for the sensitivity analysis are the decrease and increase of 5 %, 15 %, 30 %, and 50 % in each selected variable. The relative change in the output is calculated as follows:

$$c_r = \frac{(s_0 - s_1)}{s_0} \quad (1)$$

where

c_r – relative change;

s_0 – model score at the baseline scenario;

s_1 – model score under the new scenario.

These changes are presented in Fig. 4.6. The highest and lowest single score is obtained when the transport distance increases and decreases by 50 %, while a small relative change is observed as a function of energy consumption at the processor.

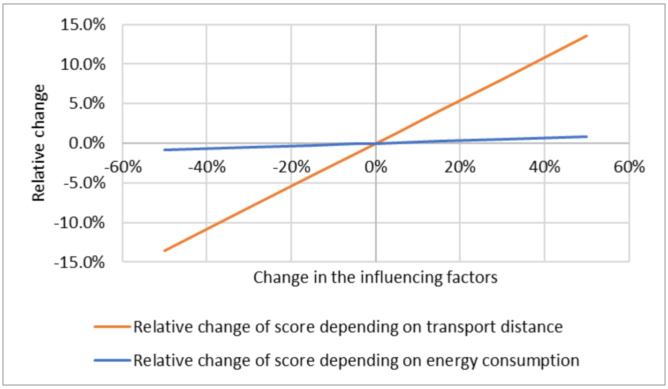


Fig. 4.6. Relative output changes depending on influencing factors.

A C-LCC evaluation compared the baseline scenario with two proposed EEMs using three economic indicators. Due to the lack of primary cost data, secondary data (budget costs) was used for the analysis (details in Article 3). Results, summarized in Table 4.5, indicate that while both EEMs show economic feasibility, EEM-1 is the most attractive option, supported by the NPV, internal rate of return (IRR), and profit index (PI) indicators.

Table 4.5

Economic Indicators Comparison in the Fish Supply Chain

Economic indicator	EEM 1	EEM 2
NPV	€ 520,786	€ 65,601
IRR	14.38 %	9.92 %
PI	1.95	1.25

The results of this case scenario demonstrate how combining LCA end-point category scores with C-LCC economic indicators can assist supply chain managers and actors in making informed decisions. However, further studies on FSCs and advanced cooling technologies are needed to fully grasp the potential for energy efficiency measures.

4.1.3. Eggs supply chain

Latvia is a key producer of eggs and egg products in Northern Europe, but no prior studies have evaluated the environmental impacts of this industry locally. To address this gap, a case study was conducted on eggs produced in Latvia and transported to European nations [225][1], using the specific product category rules (PCR) framework developed for EPDs [226]. The aim was to identify the life cycle stages with the highest environmental impact, suggest ways to mitigate these effects, and compare egg-laying types with other research.

This study assesses the entire supply chain, including chicken transport, production, packaging, and distribution to retailers, but excludes transportation to households and waste disposal. The FU is defined as 1 kg of eggs (types No. 1, No. 2, and No. 3) at the retailer, with ~ 17 eggs per kg, including packaging. Upstream processes were analyzed for mass and energy

[1]This research and Master's thesis were co-supervised by the author of this Doctoral Thesis as part of his Doctoral Research.

balances, considering waste generation at each stage following the polluters pay principle. Following the PCR methodology, the life cycle was divided as presented in Fig. 4.7.

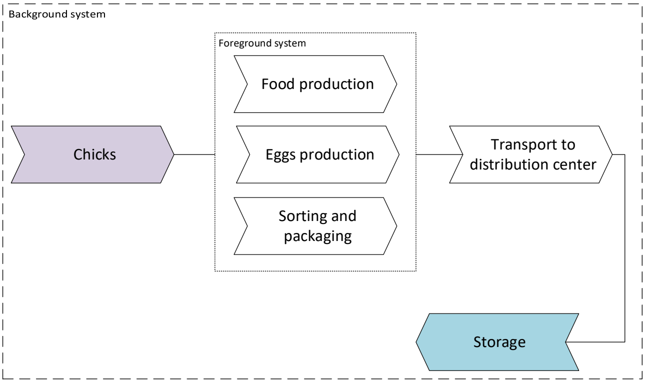


Fig. 4.7. Eggs supply chain system boundaries.

For the LCI, the company provided primary data for the three types of eggs it produces: No. 3 – cage-laid, No. 2 – barn-laid, and No. 1 – free-range eggs. The data reflects operations under their control, including details about the hens' living conditions – cages for No. 3 eggs, barn roaming for No. 2 eggs, and open-air access for No. 1 eggs, with a minimum of 4 m² of outdoor space per hen. A detailed summary of the LCI is provided in Tables 4.6–4.8.

Table 4.6

LCI of Materials per Egg Type

Inputs	Weight	Eggs No.3	Eggs No.2	Eggs No.1
Wheat	kg	1.19	1.33	1.55
Sunflower slits	kg	0.31	0.35	0.40
Barley	kg	0.29	0.32	0.37
Corn	kg	0.24	0.27	0.31
Calcium	kg	0.24	0.27	0.31
Soy	kg	0.12	0.13	0.15
Plastic boxes	kg	0.01	0.01	0.01
Paperboard boxes	kg	0.07	0.07	0.07
Transport of plastic boxes (1350 km)	kg*km	7.7	7.7	7.7
Transport of paperboard (1414 km)	kg*km	99.0	99.0	99.0

Table 4.7

Core Process LCI

Inputs	Units	Eggs No. 3	Eggs No. 2	Eggs No. 1
		Food processing		
Water	m³	3.69E-05	3.687E-05	3.67E-05
Electricity	MWh	1.64E-05	1.922E-05	1.96E-05
Natural Gas	MWh	1.03E-05	1.033E-05	1.03E-05
		Egg production		
Electricity	MWh	1.29E-04	9.972E-05	2.10E-04
Natural gas	MWh	1.23E-04	7.364E-05	5.13E-05
Water	m³	4.09E-03	3.21E-03	3.85E-03
Diesel (internal) Euro4 vehicle	l	1.40E-03	1.40E-03	1.39E-03
		Egg sorting and packaging		
Electricity	kWh	2.19E-02	2.19E-02	2.19E-02
Natural gas	kWh	1.48E-02	1.48E-02	1.48E-02
		Wastewater treatment		
Wastewater treatment	liters	6.70E-02	6.70E-02	6.70E-02

The inventory covers essential inputs such as 1-day-old chickens transported from Germany, processed grain feed, water, energy for sorting and packaging, and manure and wastewater management across the company's five locations (Bene, Jelgava, Iecava, Madona, Daugavpils). No allocation was needed; the only cut-off points were for losses: less than 1 % for chicken losses during transport, hen house egg loss, and packaging losses.

Table 4.8

Downstream Process LCI

Inputs	**Units**	**Eggs No. 3**	**Eggs No. 2**	**Eggs No. 1**
		Transport to distribution center		
Egg transport Latvia	50 km (25 %)	12.5 kg/km	12.5 kg/km	12.5 kg/km
Egg transport LT.EE	300 km (25 %)	75 kg/km	75 kg/km	75 kg/km
Egg transport EU	1500 km (50 %)	750 kg/km	750 kg/km	750 kg/km
		Manure (avoided emissions)		
Manure	l	1.55E+00	1.55E+00	1.55E+00
		Land use		
Land use	ha	0	0	2.68E-05

Main Results: The impact assessment for all three egg types, conducted using the ReCiPe 2016 method, shows that the highest environmental impacts stem from upstream activities. Significant differences were observed across the three egg types in terms of human health, ecological balance, and resource availability.

- Eggs No. 1 (free-range) had the least negative impact on human health and the ecosystem, but the highest impact on resource availability.
- Eggs No. 3 (cage-laid) had the most significant adverse effects on human health and the environment, but the least impact on resource availability.
- Eggs No. 2 (barn-laid) showed moderate effects across all three categories.

Regarding climate change impact, eggs No. 1 had a total impact of 3.58E+00 kg CO_2eq/kg eggs, while eggs No. 2 and eggs No. 3 had a total impact of 2.94E+00 kg CO_2eq/kg eggs and 2.79E+00 kg CO_2eq/kg eggs, respectively (see Fig. 4.8). This is explained by an inventory analysis, where it can be noticed that hens laying eggs No. 1 necessitated a greater amount of food, which can be linked to the wastage of feed in the free-range system and hens' higher calorific needs.

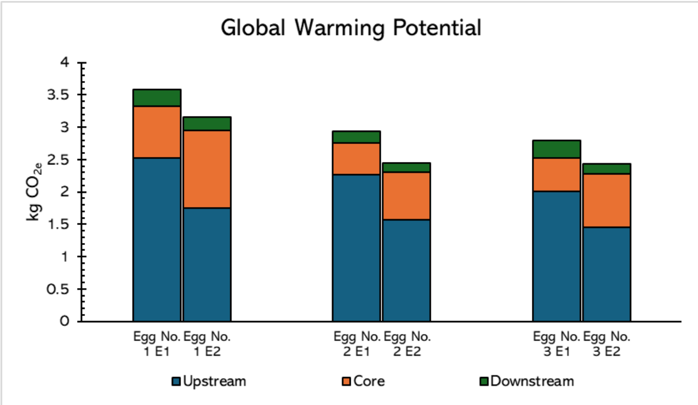


Fig. 4.8. Comparison of results in climate change are an area of concern.

4.1.4. Sustainability evaluation of food waste valorization

This case study evaluates the environmental impact of commissioning an energy recovery plant at the Mondonedo landfill in Colombia, focusing on food waste treatment. The study models an AD plant for biogas production, methane upgrading, and energy recovery, assessing environmental, economic, and social impacts through LCA, LCC, and S-LCA.

The FU is defined as 100 tons per day (36,500 tons/y). The study adopts a gate-to-gate approach, covering AD, biogas production, biomethane upgrading, and CHP while excluding sorting and recovery activities. The system boundaries are depicted in Fig. 4.9.

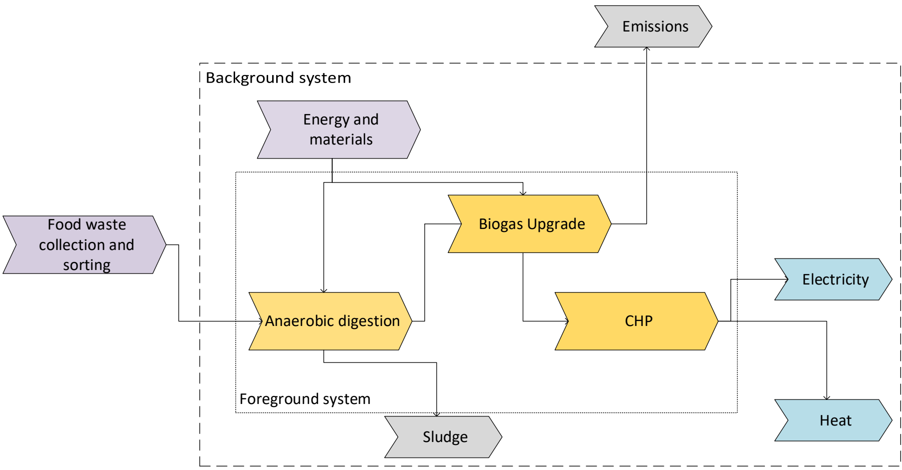


Fig. 4.9. System boundaries for FW valorization case.

The LCI includes material and energy flows, as well as the equipment and infrastructure required for production. The primary data regarding total waste, food waste composition in the waste, and degradable organic content (DOC) has been retrieved from the report for reductions of emission project of the Mondonedo landfill, considering average values for 2007–2016 [227]. For the biogas conversion, biogas upgrade to biomethane, and CHP plants operation, a process model was built in *SuperPro Designer*® to conduct mass and energy balances of all product and elementary flows (see Fig. 4.10).

Key parameters for the LCA and LCC models include calculations related to biomethane upgrading and water flows in distillation columns. The biogas produced from AD is upgraded to biomethane using water scrubbing technology, commonly applied in large systems (> 100 m³/h) [228]–[230]. This method relies on the higher solubility of CO_2 and H_2S in water than methane, following Henry's law (see Equation (2)), which describes the relationship between gas concentration in a liquid and its partial pressure [231].

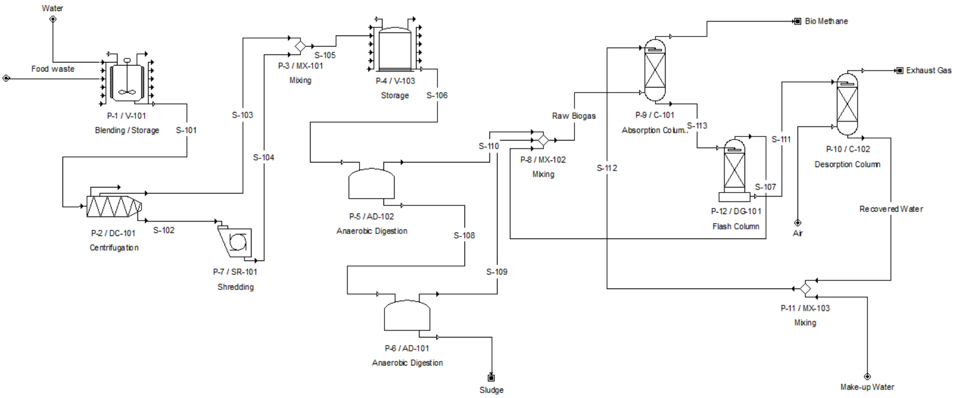


Fig. 4.10. Flow diagram for proposed technologies.

$$C_A = K_H \cdot \rho_A, \tag{2}$$

where

C_A – molar concentration of an A gas in the liquid;

K_H – Henry's constant;

ρ_A – gas's partial pressure.

Within a high-pressure absorption column (high pressure boosts the dissolubility of gases in water [232], carbon dioxide is removed from the raw biogas, dissolved into the water, and sprayed from the top of the scrubber in counter-current to the biogas. The amount of water necessary to sequestrate a certain amount of carbon dioxide, as represented in Equation (3), depends on the desired CO_2 concentration in the upgraded gas, the solubility of the carbon dioxide in the water, which is influenced by temperature and pressure in the scrubber, and by the column design [230], [231]. A full description of the detailed LCI collection can be found in Article 5.

$$Q_w(l/h) = \frac{Q_{CO2}(g)(\text{mol/h})}{C_{CO2}(aq)(\text{M})}, \quad (3)$$

where

Q_w – water flow needed in the column;

Q_{CO2} – molar flow to be removed from the biogas;

C_{CO2} – calculated carbon dioxide solubility (represented as the maximum concentration in the water) using Equation (2).

This study's C-LCC uses the same system boundaries as the LCA, modeling a full-scale plant to optimize cost efficiency through economies of scale [233]. The S-LCA evaluates stakeholders like the local community and workers, focusing on indicators such as employment, health and safety, and economic contribution [183], [234].

Main results: Environmental impacts from the food waste valorization scenario were assessed using SimaPro 9.2 and Ecoinvent v.3.7, applying the IMPACT 2002+ method [162], [163], [235], [236].

The environmental impact shared by the Mondonedo plant in the four main damage categories can be seen in Fig. 4.11. The electricity and heat production at the CHP plant generates environmental benefits that can almost compensate for the burdens created by the other stages in resource use and climate change areas of protection.

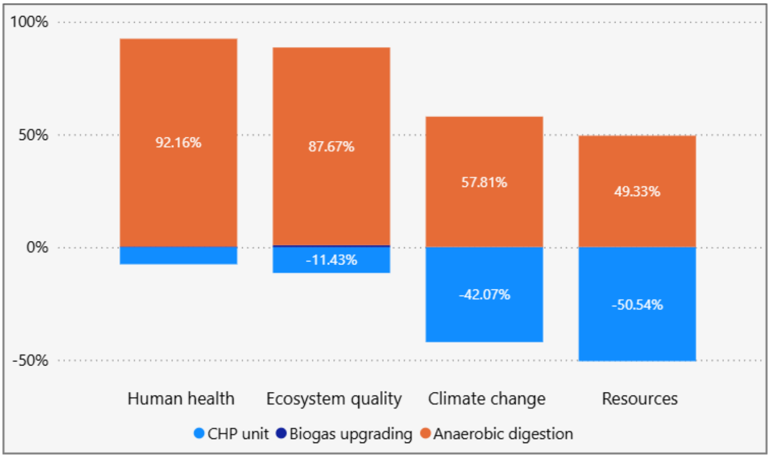


Fig. 4.11. Damage assessment results for the proposed valorization scenario.

The Mondonedo plant's total environmental impact is 506 Pt, with the main hotspot being digester sludge treatment (515 Pt), followed by the transport of sorted food waste (247 Pt), and the construction of the AD plant (79.8 Pt). Environmental benefits stem from electricity and heat production, attributed to avoided products by system expansion (see Fig. 4.12).

For socio-economic evaluation, the results showed an NPV of USD 112,248,095, an IRR of 16.25 %, and a PI of 3.43, confirming its economic viability. CAPEX and OPEX details are available in Article 5. Due to labor formalization and mandatory protective measures, biomethane cogeneration, and waste separation are expected to improve worker health and safety. However, local communities fear that those new jobs might often favor professionals from other regions.

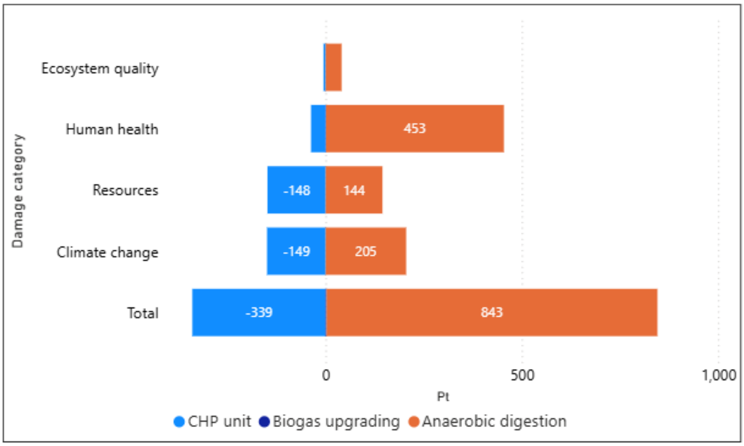


Fig. 4.12. Weighted totalized results for the proposed valorization scenarios.

4.2. Summary of different scenarios

Each case study in this research employed unique system boundaries tailored to its specific FSC, revealing distinct insights into energy efficiency and environmental impacts.

The beef cold chain case focused on processing and waste management, demonstrating that biogas recovery from anaerobic digestion could significantly reduce greenhouse gas emissions and offset energy demand. While consumer-facing stages were excluded, this approach emphasized the environmental benefits of waste-to-energy solutions.

The fishery cold supply chain study analyzed all stages, from processing to supermarket storage. It found that refrigeration contributed the most to the overall environmental impact, especially at supermarkets. The study recommended interventions like refrigerant optimization and waste valorization, showing that including the entire chain revealed energy-saving opportunities that a narrower scope might miss.

The egg production study included production and post-processing storage but excluded consumer and waste phases. It revealed that free-range eggs had a higher environmental impact due to increased calorific needs. This case focused on inefficiencies in refrigeration and packaging, offering insights without the complexity of later stages.

The food valorization case expanded to include end-of-life phases and social impacts, demonstrating that energy recovery from food waste could displace traditional power sources, providing environmental and economic benefits. This case highlighted the importance of a holistic sustainability assessment integrating circular economy principles.

These studies illustrate the strategic importance of selecting system boundaries in LCA modeling as they shape the insights gained (see Fig. 4.13). Each case showed that flexible, context-specific boundaries are essential for identifying tailored energy efficiency measures suited to the unique demands of each supply chain.

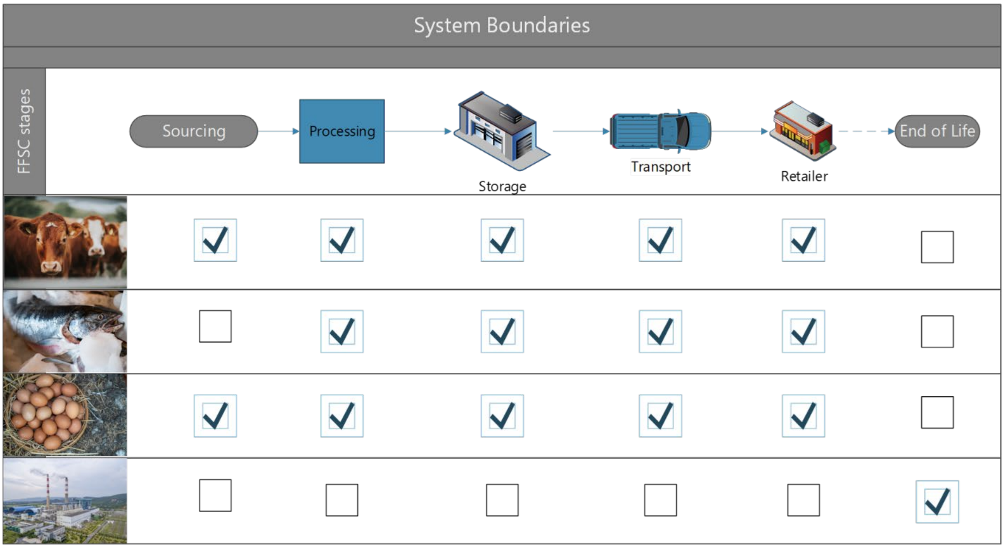


Fig. 4.13. Summary of system boundaries.

5. LIFE CYCLE SUSTAINABILITY TOOL

Developing an LCST for FSCs addresses the complexity and cost of conventional LCA. The tool streamlines evaluation of environmental, economic, and social impacts across supply chain stages, reducing reliance on costly software and specialist support. Compared with SimaPro or GaBi, a sector-focused tool lowers barriers for SMEs, identifies energy and environmental hotspots, supports benchmarking via shared assumptions and background datasets, and prioritizes energy-saving actions through a user-friendly interface. It democratizes assessment, highlights cost and emissions reductions, and supports circular economy practices, benefiting resource-limited organizations.

The LCST delivers results for global warming potential, energy demand, and water scarcity. Embedded LCC calculates NPV and IRR and incorporates social costs through GHG emissions. Built by the Thesis author, it accepts foreground activity data and uses Ecoinvent 3.6 for background data and inventory normalization. Outputs include charts, tables, and graphs to reveal hotspots. Users select products and supply chain stages for regional or global analyses, and boundaries adjust automatically.

The database covers transport vehicles, distances, fuels, storage, and waste scenarios. Data from Ecoinvent 3.6 are converted to a 1 kg functional unit. For LCC, the tool relies on user foreground data and provides editable baseline economic values. It supports conventional, environmental, and societal LCC, offering complementary perspectives for decision-making.

The tool interface is designed for usability with color-coded cells for lists, editable fields, and automatic calculations. Beyond compliance with ISO 14040 and ISO 14044, the goal is to let supply chain managers assess sustainability from an LCT perspective without expertise in LCA, LCC, or S-LCA. Users focus on accurate, consistent data entry rather than calculations.

All stages appear on a single sheet for easy tracking. Preliminary bar charts provide immediate feedback. Calculation sheets are hidden, and database libraries are protected to avoid unintended changes to conversion factors. Integration and standardization of the layout with other project tools will occur later.

The tool builds product systems by allowing selection of supply chain type (regional or global), input materials (food and packaging), transport modes, distances, travel times, payloads, energy sources, and other required inputs. Downstream waste treatment scenarios can be added for sensitivity analysis (see Fig. 5.1). Environmental impacts are quantified using three methods across three categories: GWP in CO_2 eq with IPC100a, energy intensity in MJ with cumulative energy demand, and water scarcity in m^3 with AWARE.

The LCA delivers a comprehensive view of a food chain scenario across stages and flows, with relevance at regional, national, and societal levels. The LCST thus provides a broad and detailed environmental assessment of a given supply chain.

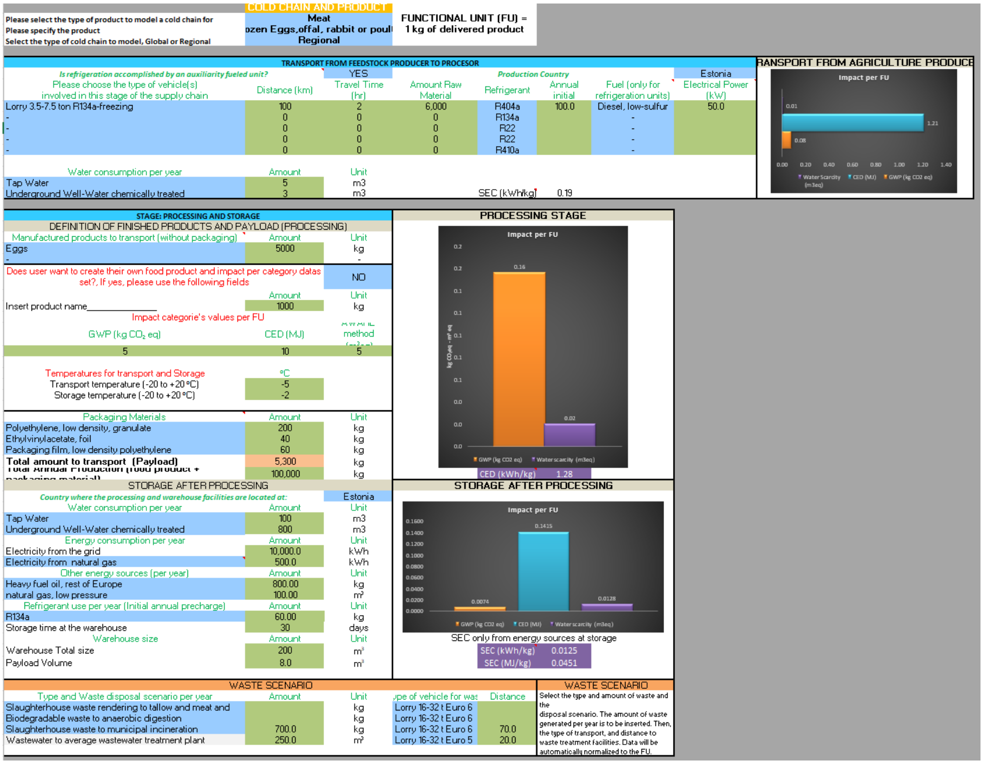


Fig. 5.1. Input parameter interface.

5.1. LCA output indicators

The LCST calculates output indicators that encapsulate all supply chain activities over a year, with the option to model single-occurrence scenarios for more advanced users. It focuses on three key environmental indicators derived from the LCA method in line with ISO 14040 and ISO 14044:

- Global warming potential (GWP): Expressed in kilograms of CO_2 equivalent, this indicator uses the IPCC 2013 method with a 100-year time horizon, capturing the life cycle emissions of materials, including extraction, raw materials, and transport, not just direct emissions [237].
- Cumulated energy demand (CED): Measured in megajoules (MJ), CED accounts for all direct and indirect energy use, considering both renewable and non-renewable sources across a product's life cycle [238], [239].
- Water scarcity: Using the AWARE methodology, this indicator measures the potential for water deprivation in cubic meters, calculating the water scarcity footprint based on regional water availability and human consumption impacts, following ISO 14046 [240].

The calculation procedure for the three impact categories included in the tool is represented by Equation (4):

$$\text{Output indicator} = \text{input value(kg)} \times \text{characterization factor} \left(\frac{\text{emissions}}{\text{kg}}\right). \quad (4)$$

The input data must be entered manually into the LCST by the user. In contrast, the tool core provides the conversion factors. The outputs can be seen either in the sheet for results or directly in the graphs presented in the user dashboard.

5.2. LCC output indicators

In the LCC evaluation within the ICCEE tool and LCST, three main LCC approaches were evaluated: conventional, environmental, and societal. Owing to the distinct methodologies employed in various kinds of LCC, diverse output indicators are utilized accordingly. The C-LCC and S-LCC exhibit notable similarities, reflected in their shared indicators. Specifically, in the context of C-LCC as adopted in the tool, the focus is predominantly on economic indicators, which include:

1. Net present value (NPV) – the difference between investment and the total present value of future net income (net cash flow).

$$NPV = \frac{R_t}{(1+i)^t}, \tag{5}$$

where

NPV – net present value;

R_t – net cash flow at time t;

i – discount rate;

t – time of the cash flow.

2. Internal rate of return (IRR) – an index illustrating the expected profit versus project investment cost. It can also be said that IRR shows the maximum loan interest rate that the project can tolerate.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0, \tag{6}$$

where

C_t – net cash flow during period t;

C_0 – total initial investment costs;

IRR – the internal rate of return;

t – the number of time periods.

3. Profit index (*PI*) – a ratio between the total present value (*PV*) of future income and initial investment.

$$PI = \frac{PV \text{ of future cash flows}}{\text{Initial investment}}, \tag{7}$$

Determining the output indicators for E-LCC assessment presents more challenges as E-LCC primarily focuses on estimating solely the economic aspect or as a broader sustainability evaluation component. Therefore, the outcomes are displayed in monetary terms for each phase of the life cycle, and this is done without applying any discounted rates.

5.3. S-LCA (S-LCC) output indicators

Similar case considerations relevant to C-LCC are also applicable to S-LCC. However, S-LCC incorporates an extra component of damage cost in assessing overall cash flows. This inclusion is based on the premise that there is a willingness to pay for the societal impacts. The output indicators for S-LCC include:

- Social NPV (SNPV): It shares the exact definition of NPV but includes additional damage costs in the evaluation.
- Social cost-benefit analysis (SCBA): It is recommended when S-LCC is conducted and is found by dividing the future scenario SNPV by the baseline scenario of SNPV. A SCBA value greater than 1.0 shows a social profit from the investment or project evaluated, while a value lower than 1.0 would show a social drawback from the project.

5.4. Data collection procedure

The foreground system focuses on specific data directly controlled by stakeholders in the supply chain, while the background system uses average data for processes not under direct control. Foreground data is primarily collected through site visits and energy audits, forming the critical input for the LCST. Background data provided by the tool supports the overall model.

The critical foreground data needed for the LCST includes:

- General company information: details like location, sector, product demand, warehouse space utilization, and peak temperature.
- Storage activities: data on production rates, warehouse temperatures, energy usage for refrigeration, water and refrigerant consumption, and packaging materials.
- Transportation operations: information on vehicle types, fuel, distances, refrigeration technology, and load capacities.
- EEMs: data on energy improvements, such as refrigeration system changes, insulation, energy recovery technologies, maintenance upgrades, and energy management systems. The LCST supports comparative analysis and standalone energy efficiency evaluations within food supply chains, integrating data on various EEMs.

Background data collection for the LCST follows ISO 14044 guidelines and focuses on gathering, organizing, and analyzing emissions and resource use data, categorized similarly to the foreground data. The main categories include:

- Transportation
    - Road transport: diesel vehicles (EURO 5 and EURO 6) for long-haul, up to 32 tons.
    - Refrigerated road transport: similar vehicles with refrigeration units powered by the main engine.
    - Global transport: trains, ships, and aircraft for transoceanic freight.
- Products and materials
    - Products: includes dairy, fish, and meat products, capturing the total environmental impact from cradle to gate.
    - Packaging materials: includes food-grade glass, polymers, and plastics.
    - Water: covers sources like underground and deionized water.

- Energy sources
    - Electricity: includes electricity from national grids in Eurozone countries and electricity generated from various fuels, such as photovoltaic and natural gas.
    - Fossil fuels: includes natural gas, oil, and coal, measured by mass/volume.
    - Biofuels: common biofuels like biogas, bioethanol, biodiesel, etc.
    - Heat: various heat sources, including cogeneration, are categorized by fuel type and plant size.
- Refrigeration materials: includes refrigerants for warehouses and transport vehicles, and fuels for independent refrigeration units.
- Waste disposal: provides disposal options for packaging materials, wastewater, slaughterhouse waste, and biodegradable substances, including transportation to the treatment facility.

All characterization factors were sourced from the Ecoinvent 3.6 database, a widely used database in commercial LCA software that complies with ISO 14044 [237].

5.5. Data input

Material and energy flows in the LCST are designed to be input on an annual basis to match the typical reporting format used in corporate frameworks. The flows include water consumption, electricity consumption, other energy sources, refrigerants (annual pre-charge), and waste materials. For example, a food company may not typically track electricity consumption for each specific product, but can easily obtain overall yearly consumption data from utility records.

Payload data is also critical in the LCST, though it is input differently from material flows. This data pertains to the mass or volume of products transported and includes key variables such as vehicle distance traveled, travel time, product volume per vehicle, refrigeration and ventilation energy for independent units, and water consumption. However, refrigerant pre-charge data must be input annually due to the environmental impact allocation based on annual leakage rates, thus necessitating alignment with this yearly method.

Additionally, data such as warehouse size, the duration a product remains in storage, payload volume, and the average yearly amount of stored products are crucial for mass and energy allocation within the tool. Accurate data input is essential, as any errors could significantly affect the calculation results.

5.6. LCA data processing and results visualization

The characterization factors used in the LCST represent the environmental impact of materials and processes within the FSC, specifically regarding GWP, CED, and water scarcity. The factors are organized into specific libraries and categorized by types of background data, as described in Subsection 5.1.4. The LCST allows users to add new agricultural products not included in the core database by providing their environmental profiles for the impact categories from a cradle-to-gate approach. Users can also adjust storage and transport conditions for these products as they move through the supply chain.

The tool processes the input data through a core Excel sheet using the stored conversion factors for each stage of the FSC. The results, shown in the LCA Results sheet, provide insights into the environmental impact of the entire cold chain, broken down by stages.

- Total impact across the three main impact categories and impact per FU for all categories is shown in Fig. 5.2.

Total impact across the cold chain	GWP (kg CO_2 eq)	CED (MJ)	Water scarcity(m^3 eq.)
	3,603	57,167	4,246

Total impact per kg transported (FU)	GWP (kg CO_2 eq)	CED (MJ)	Water scarcity (m^3 eq.)
	0.68	10.78	0.85

Fig. 5.2. Table of general outputs for LCA results.

- The chart in Fig. 5.3 shows the contribution of each stage to different impact categories , identifying environmental hotspots,

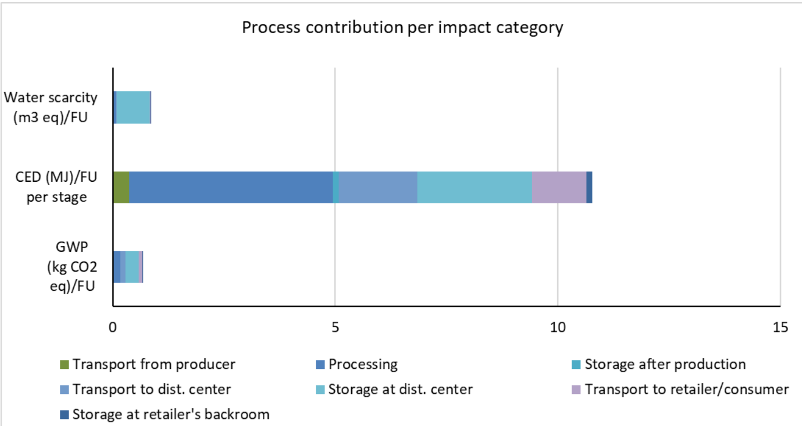


Fig. 5.3. Process contribution chart.

- Figure 5.4 presents a visual display of the process contribution to each category.

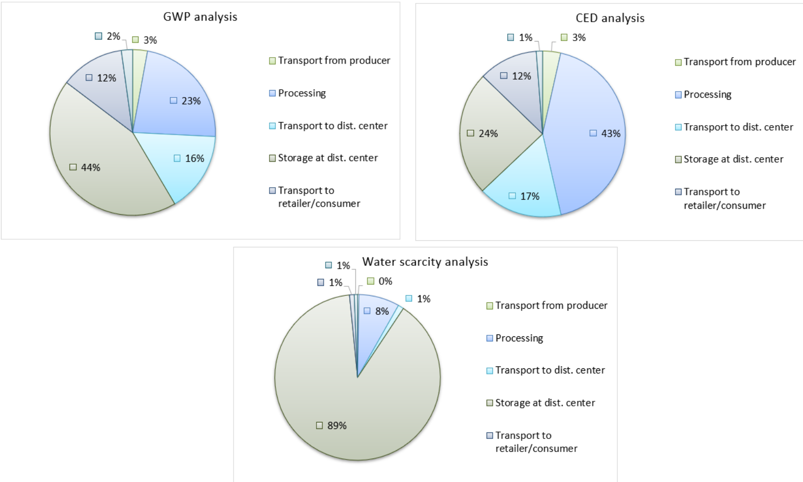


Fig. 5.4. LCA results in shares per FSC stage.

- And the cumulative impacts along the FSC stages.

5.7. LCC modeling

During this research, various EEMs across different FSC participants, including producers, transport companies, and intermediaries, were evaluated. The LCST allows users to compare up to three EEMs against a baseline scenario. Additional fields for "investment data entry" enable users to input data on project costs and EEM investment costs, which can be adjusted for different regions or markets.

Figure 5.5 illustrates the fields for project and EEM investment costs, while Fig. 5.6 shows the table for expected EEM results. EEMs usually result in energy use reductions, but the tool also allows for assessing changes in water consumption and food quality. Common EEM options include ventilation, lighting, motors, refrigeration systems, insulation improvements, and changes in staff behavior.

Project costs

Project costs			Unit	Baseline	EEM 1	EEM 2	EEM 3	Comments
Definition costs	Design (calculations, internal coordination,... etc)		€					The costs of internal expertise for the project definition phase.
	Technical assistance		€					The costs of external expertise (subcontracted) for the project definition phase.
Investement costs in EEM	Construction	Item 1	€		4,000	3,600	4,500	Correspond to the program costs required beyond the definition phase: the construction costs and the purchase and installation of equipment.
		Item 2	€					
		Item 3	€					
	Equipments and technical instalations	Item 1	€					
		Item 2	€					
		Item 3	€					
		Item 4	€					
		Item 5	€					
Running costs/cost categories	Operation and maintenance	Electricity	€/year	5,000	4,000	4,100	3,900	Costs for the activities conducted under the cold chain step assessed and directly performed by cost bearer or actor responsible for the stage (internal expertise).
		Fuels	€/year	500	493	498	510	
		Labour costs	€/year		-	-	-	
		Water	€/year		-	-	-	
		Refrigerants	€/year	20	20	20	20	
		Other	€/year					
		Vehicle maintenance	€/year					
	Production costs	Raw material 1	€/year		-	-	-	
		Raw material 2	€/year		-	-	-	
		Raw material 3	€/year		-	-	-	
		Packaging material 1	€/year		-	-	-	
		Packaging material 2	€/year		-	-	-	

Fig. 5.5. Project costs and EEMs investment costs.

The Investment Data Entry sheet captures production data and financial factors, and the C-LCC Results sheet displays the results in the discussed economic output indicators for each scenario (see Fig. 5.7).

Expected Results from EEM

Expected results/Energy savings	Unit	Baseline	-25	EEM 2	EEM 3	Comments
Change in electricity consumption	%		-5.0%	3.0%	-8.0%	
Change in other energy sources	%		0.0%	0.0%	0.0%	Corresponds to the change in the different material or energy flows, and changes in operational parameters due to EMM's implementation. Please enter the corresponding values.
Change in labour costs	%		0.0%	0.0%	0.0%	
Change in water consumption	%		0.0%	0.0%	0.0%	
Change in refrigerant pre-charge	%		-2.0%	-5.0%	-3.0%	
Change in quality factor	%		0.0%	0.0%	0.0%	Corresponds to the change in the quality factor affecting the total amount of units sold per year.Please enter the corresponding values.
Change in carbon emissions (ton CO_2 eq)	ton/year					Expected amount of carbon emission reduction

Fig. 5.6. Table for expected results from EMMs.

Additionally, the E-LCC feature calculates the cost impacts of EEMs, helping users identify the most effective cost-saving measures (see Fig. 5.8).

LIFE CYCLE COST COMPARISON (€/unit)			
Baseline	EEM 1	EEM 2	EEM 3
6.13	5.01	5.13	4.92

INVESTMENT EVALUATION COMPARISON	Baseline	EEM 1	EEM 2	EEM 3
NPV	33,721	35,587	27,509	27,940
IRR	-	115.32%	124.89%	104.65%
PI	-	9.90	8.64	7.21

NPV: Net present value is the difference between the total present value (PV) of the incoming net cash flow and the investment (–K).

IRR: Internal rate of return shows the maximum interest rate of a loan that can be tolerated by a project. If *IRR* > *WACC*, then an investment could be accepted.

PI: Profit index is a ratio between the total present value PV of future income and the initial investment.

Fig. 5.7. Visualization of C-LCC output indicators.

Please select from the droplist

In which Life cycle stage is the EEM implemented?	Transport to distribution center
Energy efficiency measure to implement?	EEM-1

Baseline scenario (€/thousands of kg delivered)						
Costs	Transport 1	Storage after processing	Transport 2	Storage at dist. center	Transport 3	Retailer backroom
Flow material cost	5.10	7.59	20.02	164.99	14.65	6.91
GWP external cost	1.60	0.42	5.97	16.64	4.75	1.45
Total E-LCC	6.70	8.02	25.99	181.63	19.40	8.36

E-LCC

Future Scenario for implementted EEM (€/thousands of kg delivered)						
Costs	Transport 1	Storage after processing	Transport 2	Storage at dist. center	Transport 3	Retailer/large consumer backroom
Flow material cost	5.10	7.59	20.13	164.99	14.65	6.91
GWP external cost	1.60	0.42	5.98	16.64	4.75	1.45
Total E-LCC	6.70	8.02	26.11	181.63	19.40	8.36

	Baseline scenario -	Future scenario (implementing EEM)
Total environmental LCC per thousand of kg transported (€)	250.10	250.22

Fig. 5.8. E-LCC results visualization.

A final feature integrating the willingness to pay for externalities usually covered by society, such as the damage caused by climate change, is included in the LCST. The user can modify this externality cost depending on the desired approach: CO_2 cost per ton as in the EU ETS, damage costs related to environmental prices, or abatement costs following the eco-costs methodology, as shown in Fig. 5.9.

Baseline scenario

Year			0	1	2	3	4	5	6	7	8	9	10	11	12	13
Outflow																
	Up-front (investment)	I	-													
	On-going (O&M)			(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)
Total standard costs		I	-	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)
Avoided damage cost		I	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Net cash flow		I	-	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)
Discount rate																
Discount factor			100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Discounted net cash flow		I	-	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)	(8,604,538)
S-LCC	$SNPV_{(b)}$	€	-	(8,604,538)	(17,209,076)	(25,813,615)	(34,418,153)	(43,022,691)	(51,627,229)	(60,231,767)	(68,836,306)	(77,440,844)	(86,045,382)	(94,649,920)	(103,254,458)	(111,858,997)

Future scenario (EEM-1)

Year			0	1	2	3	4	5	6	7	8	9	10	11	12	13
Outflow																
	Up-front (investment)	I	(26,878)													
	On-going (O&M)			(8,678,205)	(9,206,707)	(9,482,909)	(9,767,396)	(10,060,418)	(10,362,230)	(10,673,097)	(10,993,290)	(11,323,089)	(11,662,781)	(12,012,665)	(12,373,045)	(12,744,236)
Total standard costs		I	(26,878)	(8,678,205)	(9,206,707)	(9,482,909)	(9,767,396)	(10,060,418)	(10,362,230)	(10,673,097)	(10,993,290)	(11,323,089)	(11,662,781)	(12,012,665)	(12,373,045)	(12,744,236)
Avoided damage cost		I	-	5,250	5,624	5,821	6,024	6,235	6,454	6,679	6,913	7,155	7,406	7,665	7,933	8,211
Net cash flow		I	(26,878)	(8,672,955)	(9,201,083)	(9,477,088)	(9,761,371)	(10,054,182)	(10,355,777)	(10,666,418)	(10,986,377)	(11,315,934)	(11,655,376)	(12,005,000)	(12,365,112)	(12,736,025)
Discount rate	3.0%															
Discount factor			100%	97%	94%	91%	88%	85%	82%	79%	76%	73%	70%	67%	64%	61%
Discounted net cash flow		I	(26,878)	(8,412,766)	(8,649,018)	(8,624,150)	(8,590,007)	(8,546,055)	(8,491,737)	(8,426,470)	(8,349,646)	(8,260,631)	(8,158,763)	(8,043,350)	(7,913,671)	(7,768,975)
				(8,420,344)	(8,672,904)	(8,672,878)	(8,672,852)	(8,672,826)	(8,672,800)	(8,672,774)	(8,672,747)	(8,672,721)	(8,672,694)	(8,672,667)	(8,672,641)	(8,672,614)
	$SNPV_{(f)}$	€	(26,878)	(8,439,644)	(17,088,662)	(25,712,812)	(34,302,819)	(42,848,874)	(51,340,611)	(59,767,081)	(68,116,727)	(76,377,359)	(84,536,122)	(92,579,472)	(100,493,143)	(108,262,118)
S-LCC	SCBA		-	1.02	1.01	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.02	1.02	1.03	1.03

Future scenario (EEM-2)

Year			0	1	2	3	4	5	6	7	8	9	10	11	12	13
Outflow																
	Up-front (investment)	I	-													
	On-going (O&M)			(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Total standard costs		I	-	(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Avoided damage cost		I	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Net cash flow		I	-	(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Discount rate	3.0%															
Discount factor			100%	97%	94%	91%	88%	85%	82%	79%	76%	73%	70%	67%	64%	61%
Discounted net cash flow		I	-	(8,346,402)	(8,580,841)	(8,556,194)	(8,522,346)	(8,478,765)	(8,424,900)	(8,360,172)	(8,283,978)	(8,195,689)	(8,094,646)	(7,980,164)	(7,851,529)	(7,707,993)
	$SNPV_{(f)}$	€	-	(8,346,402)	(16,927,243)	(25,483,438)	(34,005,783)	(42,484,548)	(50,909,449)	(59,269,621)	(67,553,599)	(75,749,288)	(83,843,934)	(91,824,098)	(99,675,627)	(107,383,621)
S-LCC	SCBA		#DIV/0!	1.03	1.02	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04	1.04

Future scenario (EEM-3)

Year			0	1	2	3	4	5	6	7	8	9	10	11	12	13
Outflow																
	Up-front (investment)	I	-													
	On-going (O&M)			(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Total standard costs		I	-	(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Avoided damage cost		I	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Net cash flow		I	-	(8,604,538)	(9,128,555)	(9,402,411)	(9,684,484)	(9,975,018)	(10,274,269)	(10,582,497)	(10,899,972)	(11,226,971)	(11,563,780)	(11,910,693)	(12,268,014)	(12,636,054)
Discount rate	3.0%															
Discount factor			100%	97%	94%	91%	88%	85%	82%	79%	76%	73%	70%	67%	64%	61%
Discounted net cash flow		I	-	(8,346,402)	(8,580,841)	(8,556,194)	(8,522,346)	(8,478,765)	(8,424,900)	(8,360,172)	(8,283,978)	(8,195,689)	(8,094,646)	(7,980,164)	(7,851,529)	(7,707,993)
	$SNPV_{(f)}$	€	-	(8,346,402)	(16,927,243)	(25,483,438)	(34,005,783)	(42,484,548)	(50,909,449)	(59,269,621)	(67,553,599)	(75,749,288)	(83,843,934)	(91,824,098)	(99,675,627)	(107,383,621)
S-LCC	SCBA		#DIV/0!	1.03	1.02	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04	1.04

Fig. 5.9. S-LCC results visualization.

5.8. Tool validation

The tool validation took place through the ICCEE project, which targeted SMEs for decision-making around EEMs. The validation followed the following processes.

- Conceptual Tool Validation:
- Data was collected from various supply chain stakeholders, such as suppliers, producers, and retailers, during earlier project stages. This data validated several tools, focusing on the supply chain's energy consumption, lifecycle analysis, and benchmarking.
- The tool was tested using real-world supply chain data, although it was noted that not all datasets were complete enough to model entire cases.
- Each tool underwent rigorous technical validation, including system and user acceptance tests, to ensure usability, functionality, and the absence of bugs.
- A group of energy managers and industry experts were asked to provide feedback on both the user interface and the presentation of the results. Each project partner was assigned specific tools to test, ensuring coverage across the suite of tools developed.

The results from the validation protocol were the following:

- Positive feedback: Most users found the tools useful, with some expressing interest in using them in the future. The general usability and user-friendliness of the tools were praised, and no major data inconsistencies were reported.
- Identified issues: Minor formatting issues were noted, such as cell width adjustments and problems with drop-down menus. Additionally, some translation inconsistencies and suggestions to change units to more intuitive measures were highlighted.
- Content recommendations: There were requests to expand the drop-down menu options and clarify some instructions. The LCA tool required adjustments to calculation formulas, while others needed improvements in result presentation.

In general, the tool was well-received and provided a valuable resource for companies in the cold supply chain sector to improve energy efficiency. Some minor adjustments and bug fixes were required, but the tool met the validation criteria overall.

6. CONCLUSIONS AND RECOMMENDATIONS

Over the past five decades, sustainability has shifted from a needs-based concept to an integrated approach that elevates ecological and social values alongside economic ones. Sustainable development now centers on human well-being and environmental integrity, not growth alone.

In the food industry, globalization has lengthened and complicated supply chains, increasing energy use, resource consumption, and food waste. Quantitative assessment still lacks a cohesive framework that integrates environmental, social, and economic pillars. Life cycle thinking addresses this by evaluating impacts across the full life cycle, yet practical, accessible tools remain scarce, particularly for sector-specific needs and SMEs.

This research developed and tested a life cycle sustainability tool through case studies in beef, fish, and egg chains. The tool integrates the three pillars, identifies hotspots, and evaluates trade-offs and interventions. Some of the findings can be summarized as follows:

- LCA results show higher per-kilogram impacts in globalized beef chains, supporting local sourcing;
- fishing activities driven by fossil fuels and inefficient retail storage dominate fish impacts;
- transport distances significantly shape footprints;
- targeted energy efficiency measures in egg supply chains deliver gains even at a small scale.

Economic analyses confirm that energy efficiency investments are both environmentally beneficial and financially sound. The LCST provides actionable insights for producers, supply chain managers, and policymakers, supporting strategy design, resource allocation, and the development of effective policy frameworks.

6.1. Conclusions related to the objectives

This research addressed the lack of a standardized, practical framework that integrates environmental, economic, and social pillars into a single quantitative assessment for the food industry. By operationalizing life cycle thinking in a robust, user-friendly way, the Thesis shows that fragmented evaluations can be replaced with a holistic methodology.

A central conclusion is that LCA can be simplified without losing rigor. The proposed LCST integrates LCA, LCC, and selected S-LCA indicators, standardizing use, so non-experts, including SMEs, can design and evaluate supply chains with minimal prior knowledge.

Case studies in beef, fish, and egg chains confirm the tool's utility. Results identify hotspots and guide interventions: high burdens from long-distance transport in beef supply chains, energy-intensive fishing operations in fish supply chains, and targeted efficiency opportunities in egg production. Outputs inform producers on process improvements, help managers prioritize investments, and indicate where policy incentives can be most effective.

The LCST bridges theory and practice by translating LCT principles into a standardized yet adaptable tool that balances scientific rigor with usability. This is timely given that new European regulations, such as CSRD, ESPR, CBAM, and CPR, are emerging, increasing requirements for credible performance evaluation and reporting.

Overall, integrating LCA, LCC, and S-LCA into a simplified, standardized methodology is feasible and necessary. By demonstrating the operationalization of LCT through empirical applications, the Thesis provides both theoretical advancement and a practical instrument for decision-making across the food supply chain.

6.2. Recommendations

The LCST developed in this Thesis enables rapid sustainability evaluation for food supply chains across most EU-27 countries. Simplifying the ISO 14040/14044 LCA approach reduces complexity while preserving rigor. Users can build product systems, adjust system boundaries, and obtain results without prior LCA expertise. The tool applies gate-to-gate boundaries while still considering relevant upstream and selected downstream processes.

For industry and supply chain managers, the LCST offers a practical decision-support tool. Integrated LCA and LCC modules allow analysis of environmental and economic trade-offs, and social indicators extend coverage to all three pillars. Usability supports large firms and SMEs; brief training is advised to avoid errors and ensure consistent results.

Benefits extend beyond environmental gains. The LCST helps identify measures that reduce vehicle use or shift to more efficient fleets, optimize energy in refrigeration and processing, support regulatory compliance, and cut costs from waste and resource inefficiency. Results also strengthen sustainability communication with consumers, clients, and investors.

Experience from the ICCEE project shows firms can capture energy efficiency and non-energy benefits. Benchmarking and capacity-building (training and e-learning) helped translate assessments into action. Future LCST dissemination should include targeted training to embed sustainability practices.

For policymakers, simplified and standardized tools like the LCST should be incorporated into policy and regulatory instruments to lower compliance barriers and broaden adoption. Quantitative outputs can guide targeted measures, such as incentivizing local sourcing, upgrading refrigeration efficiency, and reducing fossil fuel dependence in fisheries.

For academia, the LCST is a teaching and training resource for students and practitioners without advanced LCA training. Embedding it in curricula and workshops will help bridge theory and industrial practice.

In sum, adopting the LCST in industry, integrating it into policy, and using it in education can reduce environmental burdens, improve economic efficiency, and reinforce social responsibility across food supply chains.

6.3. Recommendations for Future Research

In addition to these practical, policy, and educational applications, this Thesis highlights several avenues for future research. First, there is a need to further refine the integration of the social dimension into LCT-based tools. While environmental and economic pillars are relatively well developed, social sustainability remains less standardized and requires methodological innovation, particularly in capturing supply chain-level issues such as labor rights, community well-being, and fair trade practices.

Second, future research should aim to extend the LCST framework beyond the food industry to test its adaptability in other sectors characterized by complex supply chains, such as textiles, construction, or pharmaceuticals. Comparative studies would allow researchers to assess both the universality and sector-specific limitations of the methodology.

Third, as digitalization and big data analytics continue to evolve, integrating real-time data streams, blockchain-based traceability, and artificial intelligence into life cycle sustainability assessment tools will be essential. Such integration could significantly reduce data gaps and enhance the accuracy, scalability, and dynamic updating of results.

Fourth, further research is needed to explore how the LCST can be combined with planetary boundaries and absolute sustainability concepts in a more systematic way. Although this Thesis introduces steps in this direction, operationalizing global limits into product- and process-level decision-support tools remains a frontier in sustainability science.

BIBLIOGRAPHY

[1] R. Hernández Sampieri and C. F. Fernandez-Collado, *Metodología de la investigación*, Sexta edición. México D.F.: McGraw-Hill Education, 2014.

[2] WCED, "Our common future. Oxford: Oxford University Press," 1987.

[3] M. Diesendorf, "Sustainability and sustainable development," in *Sustainability: The corporate challenge of the 21st century*, Epping, 2000, pp. 19–37. [Online]. Available: http://markdiesendorf.com/wp-content/uploads/2015/09/CorpSust2000.pdf

[4] T. Snegireva, G. Kayachev, A. Falaleev, and S. Kurgansky, "Human potential in the system of sustainable development," in *E3S web of conferences*, 2019. doi: 10.1051/e3sconf/201913403014.

[5] A. Romeiro, "Sustainable development: an ecological economics perspective," 2013.

[6] J. Rockström *et al.*, "A safe operating space for humanity," *Nature*, vol. 461, no. 7263, Art. no. 7263, Sep. 2009, doi: 10.1038/461472a.

[7] K. Raworth, "A Doughnut for the Anthropocene: humanity's compass in the 21st century," *The Lancet Planetary Health*, vol. 1, no. 2, pp. e48–e49, May 2017, doi: 10.1016/S2542-5196(17)30028-1.

[8] L. Persson *et al.*, "Outside the Safe Operating Space of the Planetary Boundary for Novel Entities," *Environ. Sci. Technol.*, vol. 56, no. 3, pp. 1510–1521, Feb. 2022, doi: 10.1021/acs.est.1c04158.

[9] K. Richardson *et al.*, "Earth beyond six of nine planetary boundaries," *Sci. Adv.*, vol. 9, no. 37, p. eadh2458, Sep. 2023, doi: 10.1126/sciadv.adh2458.

[10] J. Rockström *et al.*, "Safe and just Earth system boundaries," *Nature*, vol. 619, no. 7968, Art. no. 7968, Jul. 2023, doi: 10.1038/s41586-023-06083-8.

[11] A. Bjørn, M. Diamond, M. Owsianiak, B. Verzat, and M. Z. Hauschild, "Strengthening the Link between Life Cycle Assessment and Indicators for Absolute Sustainability To Support Development within Planetary Boundaries," *Environ. Sci. Technol.*, vol. 49, no. 11, pp. 6370–6371, Jun. 2015, doi: 10.1021/acs.est.5b02106.

[12] FoodDrinkEurope, "EU Food and Drink Industry," 2016. Accessed: Jan. 12, 2024. [Online]. Available: https://www.triptolemos.org/wp-content/uploads/2017/02/0184_2016_IA_Dades-agroalimentaria-UE-2015.pdf

[13] Deloitte, "Energy efficiency in Europe – The levers to deliver the potential," Deloitte, 2016. Accessed: Jan. 12, 2024. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/energy-efficiency-in-europe.pdf

[14] D. Coulomb, "Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment," *Trends in Food Science & Technology*, vol. 19, no. 8, pp. 413–417, Aug. 2008, doi: 10.1016/j.tifs.2008.03.006.

[15] G. Liu, "The impact of supply chain relationship on food quality," *Procedia Computer Science*, vol. 131, pp. 860–865, 2018, doi: 10.1016/j.procs.2018.04.286.

[16] M. M. Aung and Y. S. Chang, "Traceability in a food supply chain: Safety and quality perspectives," *Food Control*, vol. 39, no. 1, pp. 172–184, 2014, doi: 10.1016/j.foodcont.2013.11.007.

[17] S. H. Gheewala, N. Jungbluth, B. Notarnicola, B. Ridoutt, and H. van der Werf, "No simple menu for sustainable food production and consumption," *Int. J. Life Cycle Assess.*, vol. 25, no. 7, pp. 1175–1182, Jul. 2020, doi: 10.1007/s11367-020-01783-z.

[18] FAO, "The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction," in *the State of the World*, 2016, pp. 1–439.

[19] C. Arias Bustos and E. H. M. Moors, "Reducing post-harvest food losses through innovative collaboration: Insights from the Colombian and Mexican avocado supply chains," *Journal of Cleaner Production*, vol. 199, pp. 1020–1034, 2018, doi: 10.1016/j.jclepro.2018.06.187.

[20] United Nations, "The sustainable development goals report 2019," *United Nations publication issued by the Department of Economic and Social Affairs*, p. 64, 2019.

[21] M. del C. Alamar, N. Falagán, E. Aktas, and L. A. Terry, "Minimising food waste: a call for multidisciplinary research," *Journal of the Science of Food and Agriculture*, 2018, doi: 10.1002/jsfa.8708.

[22] C. Beretta, F. Stoessel, U. Baier, and S. Hellweg, "Quantifying food losses and the potential for reduction in Switzerland," *Waste Management*, 2013, doi: 10.1016/j.wasman.2012.11.007.

[23] "A systematic literature review of food sustainable supply chain management (FSSCM): building blocks and research trends | Emerald Insight." Accessed: Jan. 01, 2024. [Online]. Available: https://www.emerald.com/insight/content/doi/10.1108/TQM-10-2021-0300/full/html

[24] A. Guo, S. Bryngelsson, A. Strid, M. Bianchi, A. Winkvist, and E. Hallström, "Choice of health metrics for combined health and environmental assessment of foods and diets: A systematic review of methods," *Journal of Cleaner Production*, vol. 365. 2022. doi: 10.1016/j.jclepro.2022.132622.

[25] S. Ammirato, A. M. Felicetti, M. Ferrara, C. Raso, and A. Violi, "Collaborative Organization Models for Sustainable Development in the Agri-Food Sector," *Sustainability*, vol. 13, no. 4, p. 2301, 2021, doi: 10.3390/su13042301.

[26] M. J. Page *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.

[27] Y. Chiffoleau and T. Dourian, "Sustainable Food Supply Chains: Is Shortening the Answer? A Literature Review for a Research and Innovation Agenda," *Sustainability*, vol. 12, no. 23, p. 9831, 2020, doi: 10.3390/su12239831.

[28] L. Shamseer *et al.*, "Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation," *BMJ*, vol. 349, pp. 1–25, Jan. 2015, doi: 10.1136/bmj.g7647.

[29] G. Brunori and F. Galli, "Sustainability of local and global food chains: Introduction to the special issue," *Sustainability (Switzerland)*, vol. 8, no. 8. 2016. doi: 10.3390/su8080765.

[30] S. Ahmad and K. Wong, "A Comprehensive and Integrated Stochastic-Fuzzy Method for Sustainability Assessment in the Malaysian Food Manufacturing Industry," *Sustainability*, vol. 11, no. 4, p. 948, Feb. 2019, doi: 10.3390/su11040948.

[31] A. Bjorn *et al.*, "A comprehensive planetary boundary-based method for the nitrogen cycle in life cycle assessment: Development and application to a tomato production case study." Accessed: Dec. 22, 2022. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S0048969720303235?token=23A7616CCB8DC5C94FC35513641ABEC8A45499DEEE391B96DE8C5A582F8032C9E05525D2A11B997FEAA430419392E5A5&originRegion=eu-west-1&originCreation=20221222110904

[32] M. Kucukvar, N. C. Onat, G. M. Abdella, and O. Tatari, "Assessing regional and global environmental footprints and value added of the largest food producers in the world," *Resources, Conservation and Recycling*, vol. 144, pp. 187–197, 2019. doi: 10.1016/j.resconrec.2019.01.048.

[33] A. Avadí, P. Fréon, and J. Tam, "Coupled ecosystem/supply chain modelling of fish products from sea to shelf: The Peruvian anchoveta case," *PLoS ONE*, vol. 9, no. 7, 2014. doi: 10.1371/journal.pone.0102057.

[34] M. Al-Obadi, "Dairy Wastage Footprint Analysis: A Farm-to-Fork Life Cycle Approach Across Dairy Supply Chain.," *Proceedings of the International Conference on Industrial Engineering and Operations Management*. pp. 200–211, 2021. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85130250902&partnerID=40&md5=e23f93022cf47e97afeb4137dd99b90b

[35] T. Winkler and R. Aschemann, "Decreasing greenhouse gas emissions of meat products through food waste reduction. A framework for a sustainability assessment approach," *Food Waste Reduction and Valorisation: Sustainability Assessment and Policy Analysis,* 2017. doi: 10.1007/978-3-319-50088-1_4.

[36] A. K. Farmery, C. Gardner, B. S. Green, S. Jennings, and R. A. Watson, "Domestic or imported? An assessment of carbon footprints and sustainability of seafood consumed in Australia," *Environmental Science and Policy*, vol. 54, pp. 35–43, 2015. doi: 10.1016/j.envsci.2015.06.007.

[37] G. Garcia-Garcia, L. Azanedo, and S. Rahimifard, "Embedding sustainability analysis in new food product development," *Trends in Food Science and Technology*, vol. 108, pp. 236–244, 2021. doi: 10.1016/j.tifs.2020.12.018.

[38] R. Stefanini and G. Vignali, "Environmental and economic sustainability assessment of an industry 4.0 application: the AGV implementation in a food industry," *International Journal of Advanced Manufacturing Technology*, vol. 120, no. 5–6, pp. 2937–2959, 2022. doi: 10.1007/s00170-022-08950-6.

[39] Preethi, S. Kavitha, J. R. Banu, P. Arulazhagan, and M. Gunasekaran, "Environmental impacts and sustainability assessment of food loss and waste valorization: Value chain analysis of food consumption," *Food Waste to Valuable Resources: Applications and Management,* 2020. doi: 10.1016/B978-0-12-818353-3.00017-1.

[40] M. Dreyer *et al.*, "Environmental life cycle assessment of yellow mealworm (Tenebrio molitor) production for human consumption in Austria – a comparison of mealworm and broiler as protein source," *International Journal of Life Cycle Assessment*, vol. 26, no. 11. pp. 2232–2247, 2021. doi: 10.1007/s11367-021-01980-4.

[41] V. Uusitalo, A. Kuokkanen, K. Grönman, N. Ko, H. Mäkinen, and K. Koistinen, "Environmental sustainability assessment from planetary boundaries perspective – A case study of an organic sheep farm in Finland," *Science of the Total Environment*, vol. 687, pp. 168–176, 2019. doi: 10.1016/j.scitotenv.2019.06.120.

[42] M. Cooreman-Algoed, L. Boone, S. E. Taelman, S. Van Hemelryck, A. Brunson, and J. Dewulf, "Impact of consumer behaviour on the environmental sustainability profile of food production and consumption chains – a case study on chicken meat," *Resources, Conservation and Recycling*, vol. 178, 2022. doi: 10.1016/j.resconrec.2021.106089.

[43] S. Cristiano, H. Baarset, C. Bruckner, J. Johansen, and R. Pastres, “Innovative options for the reuse and valorisation of aquaculture sludge and fish mortalities: Sustainability evaluation through Life-Cycle Assessment,” *Journal of Cleaner Production*, vol. 352, 2022. doi: 10.1016/j.jclepro.2022.131613.
[44] S. Ahmad, K. Y. Wong, and R. Ahmad, “Life cycle assessment for food production and manufacturing: Recent trends, global applications and future prospects,” vol. 34, pp. 49–57, 2019. doi: 10.1016/j.promfg.2019.06.113.
[45] F. Ziegler *et al.*, “Local seal or imported meat? Sustainability evaluation of food choices in greenland, based on life cycle assessment,” *Foods*, vol. 10, no. 6, 2021. doi: 10.3390/foods10061194.
[46] G. Egilmez, M. Kucukvar, O. Tatari, and M. K. S. Bhutta, “Supply chain sustainability assessment of the U.S. food manufacturing sectors: A life cycle-based frontier approach,” *Resources, Conservation and Recycling*, vol. 82, pp. 8–20, Jan. 2014, doi: 10.1016/j.resconrec.2013.10.008.
[47] G. M. Abdella *et al.*, “Sustainability assessment and modeling based on supervised machine learning techniques: The case for food consumption,” *Journal of Cleaner Production*, vol. 251, p. 119661, Apr. 2020. doi: 10.1016/j.jclepro.2019.119661.
[48] P. Bergström, C. Malefors, I. Strid, O. J. Hanssen, and M. Eriksson, “Sustainability assessment of food redistribution initiatives in Sweden,” *Resources*, vol. 9, no. 3, 2020. doi: 10.3390/resources9030027.
[49] S. Rafiee, B. Khoshnevisan, I. Mohammadi, M. Aghbashlo, H. mousazadeh, and S. Clark, “Sustainability evaluation of pasteurized milk production with a life cycle assessment approach: An Iranian case study,” *Science of the Total Environment*, vol. 562, pp. 614–627, 2016. doi: 10.1016/j.scitotenv.2016.04.070.
[50] K. Shahzad, M. Rehan, M. I. Rashid, N. Ali, A. S. Summan, and I. M. I. Ismail, “Sustainability evaluation of polyhydroxyalkanoate production from slaughterhouse residues utilising emergy accounting,” *Polymers*, vol. 14, no. 1, 2022. doi: 10.3390/polym14010118.
[51] N. Yakovleva, J. Sarkis, and T. W. Sloan, “Sustainability indicators for the food supply chain,” in *Environmental Assessment and Management in the Food Industry*, Elsevier, 2010, pp. 297–329. doi: 10.1533/9780857090225.3.297.
[52] J. Schwarz, M. Schuster, B. Annaert, M. Maertens, Erik Mathijs, and E. Mathijs, “Sustainability of global and local food value chains. An empirical comparison of Peruvian and Belgian asparagus,” Mar. 2016.
[53] S. M. Ioannidou *et al.*, “Sustainable production of bio-based chemicals and polymers via integrated biomass refining and bioprocessing in a circular bioeconomy context,” *Bioresource Technology*, vol. 307, 2020. doi: 10.1016/j.biortech.2020.123093.
[54] H. Rohn, M. Lukas, K. Bienge, J. Ansorge, and C. Liedtke, “The hot spot analysis: Utilization as customized management tool towards sustainable value chains of companies in the food sector,” *Agris On-line Papers in Economics and Informatics*, vol. 6, no. 4, pp. 133–143, 2014.
[55] A. Dobon *et al.*, “The sustainability of communicative packaging concepts in the food supply chain. A case study: Part 2. Life cycle costing and sustainability assessment,” *International Journal of Life Cycle Assessment*, vol. 16, no. 6, pp. 537–547, 2011. doi: 10.1007/s11367-011-0291-9.
[56] A. Melkonyan, K. Krumme, T. Gruchmann, and G. De La Torre, “Sustainability assessment and climate change resilience in food production and supply,” *Energy Procedia*, vol. 123, pp. 131–138, 2017. doi: 10.1016/j.egypro.2017.07.236.
[57] A. Melkonyan, T. Gruchmann, F. Lohmar, V. Kamath, and S. Spinler, “Sustainability assessment of last-mile logistics and distribution strategies: The case of local food networks,” *International Journal of Production Economics*, vol. 228, 2020. doi: 10.1016/j.ijpe.2020.107746.
[58] G. Brunori *et al.*, “Are local food chains more sustainable than global food chains? Considerations for Assessment,” *Sustainability (Switzerland)*, vol. 8, no. 5, 2016. doi: 10.3390/su8050449.
[59] C. Peano, N. Tecco, E. Dansero, V. Girgenti, and F. Sottile, “Evaluating the sustainability in complex agri-food systems: The SAEMETH framework,” *Sustainability (Switzerland)*, vol. 7, no. 6, pp. 6721–6741, 2015. doi: 10.3390/su7066721.
[60] A. M. Gómez-Trujillo and I. C. A. Rendón, “International presence and sustainability in emerging markets: Nutresa Group towards a global leadership; [Presencia internacional y sostenibilidad en mercados emergentes: Grupo Nutresa hacia un liderazgo global],” *Produccion y Limpia*, vol. 14, no. 1, pp. 77–93, 2019. doi: 10.22507/pml.v14n1a4.
[61] A. Doernberg, A. Piorr, I. Zasada, D. Wascher, and U. Schmutz, “Sustainability assessment of short food supply chains (SFSC): developing and testing a rapid assessment tool in one African and three European city regions,” *Agriculture and Human Values*, vol. 39, no. 3, pp. 885–904, 2022. doi: 10.1007/s10460-021-10288-w.
[62] A. Woodhouse, J. Davis, C. Pénicaud, and K. Östergren, “Sustainability checklist in support of the design of food processing,” *Sustainable Production and Consumption*, vol. 16, pp. 110–120, 2018. doi: 10.1016/j.spc.2018.06.008.

[63] D. Marino, L. Mastronardi, A. Giannelli, V. Giaccio, and G. Mazzocchi, "Territorialisation dynamics for Italian farms adhering to Alternative Food Networks," *Bulletin of Geography. Socio-economic Series*, no. 40, Art. no. 40, Jun. 2018, doi: 10.2478/bog-2018-0018.
[64] E. Bottani, M. C. Gentilotti, and M. Rinaldi, "A fuzzy logic-based tool for the assessment of corporate sustainability: A case study in the food machinery industry," *Sustainability (Switzerland)*, vol. 9, no. 4, 2017. doi: 10.3390/su9040583.
[65] E. Sharifi, S. H. Amin, and L. Fang, "A new fuzzy group decision-making approach for evaluating sustainability of food supply chains," *IISE Annual Conference and Expo 2021*, pp. 199–204, 2021. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85120932241&partnerID=40&md5=ead427d0f02beb3529572821435d8c71
[66] M. Yani *et al.*, "An Adaptive Fuzzy Multi-Criteria Model for Sustainability Assessment of Sugarcane Agroindustry Supply Chain," *IEEE Access*, vol. 10, pp. 5497–5517, 2022. doi: 10.1109/ACCESS.2022.3140519.
[67] V. Sridharan and M. Suresh, "Environmental sustainability assessment using multigrade fuzzy-A case of two Indian colleges," *2016 IEEE International Conference on Computational Intelligence and Computing Research, ICCIC 2016*. 2016. doi: 10.1109/ICCIC.2016.7919594.
[68] Mukesh Kumar, M. Sharma, R. D. Raut, S. K. Mangla, and Vikas Kumar Choubey, "Performance assessment of circular driven sustainable agri-food supply chain towards achieving sustainable consumption and production," *Journal of Cleaner Production*, vol. 372, pp. 133698–133698, Oct. 2022, doi: 10.1016/j.jclepro.2022.133698.
[69] C J Siddegowda and A. Jayanthila Devi, "A Study on the Role of Precision Agriculture in Agro-Industry," vol. 5, no. 2, pp. 57–67, Sep. 2021, doi: 10.47992/ijaeml.2581.7000.0103.
[70] A. Kumar, S. K. Mangla, and P. Kumar, "An integrated literature review on sustainable food supply chains: Exploring research themes and future directions," *Science of the Total Environment*, vol. 821, 2022. doi: 10.1016/j.scitotenv.2022.153411.
[71] W. A. P. Dania, K. Xing, and Y. Amer, "Collaboration and Sustainable Agri-Food Supply Chain: A Literature Review," vol. 58, p. 02004, Jan. 2016. doi: 10.1051/matecconf/20165802004.
[72] R. Küchler and C. Herzig, "Connectivity is key: holistic sustainability assessment and reporting from the perspective of food manufacturers," *British Food Journal*, vol. 123, no. 9, pp. 3154–3171, 2021. doi: 10.1108/BFJ-03-2021-0317.
[73] C. Moreno-Miranda and L. Dries, "Integrating coordination mechanisms in the sustainability assessment of agri-food chains: From a structured literature review to a comprehensive framework," *Ecological Economics*, vol. 192, 2022. doi: 10.1016/j.ecolecon.2021.107265.
[74] A. M. Faus, A. Moragues-Faus, and A. Marceau, "Measuring Progress in Sustainable Food Cities: An Indicators Toolbox for Action," *Sustainability*, vol. 11, no. 1, p. 45, Dec. 2018, doi: 10.3390/su11010045.
[75] E. Desiderio, L. García-Herrero, D. Hall, A. Segrè, and M. Vittuari, "Social sustainability tools and indicators for the food supply chain: A systematic literature review," *Sustainable Production and Consumption*, vol. 30, pp. 527–540, 2022. doi: 10.1016/j.spc.2021.12.015.
[76] Shamraiz Ahmad, Kuan Yew Wong, and Shahid Ikramullah Butt, "Status of sustainable manufacturing practices: literature review and trends of triple bottom-line-based sustainability assessment methodologies," *Environmental Science and Pollution Research*, Jul. 2022, doi: 10.1007/s11356-022-22172-z.
[77] J. G. A. J. van der Vorst, L. Peeters, and J. M. Bloemhof, "Sustainability Assessment Framework for Food Supply Chain Logistics: Empirical Findings from Dutch Food Industry," *International Journal on Food System Dynamics*, vol. 4, no. 2, pp. 130–139, 2013. doi: 10.18461/ijfsd.v4i2.424.
[78] H. El Bilali, C. Strassner, and T. Ben Hassen, "Sustainable agri-food systems: Environment, economy, society, and policy," *Sustainability (Switzerland)*, vol. 13, no. 11, 2021. doi: 10.3390/su13116260.
[79] E. Slätmo, Elin Slätmo, K. Fischer, and E. Röös, "The Framing of Sustainability in Sustainability Assessment Frameworks for Agriculture," *Sociologia Ruralis*, vol. 57, no. 3, pp. 378–395, Jul. 2017, doi: 10.1111/soru.12156.
[80] C. Silvestri, L. Silvestri, M. Piccarozzi, and Alessandro Ruggieri, "Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: a systematic literature review," *International Journal of Life Cycle Assessment*, Mar. 2022. doi: 10.1007/s11367-022-02032-1.
[81] F. Galli *et al.*, "Sustainability assessment of food supply chains: an application to local and global bread in Italy," *Agricultural and Food Economics*, vol. 3, no. 1, 2015. doi: 10.1186/s40100-015-0039-0.
[82] V. León Bravo, A. Moretto, and F. Caniato, "A roadmap for sustainability assessment in the food supply chain," *British Food Journal*, vol. 123, no. 13, pp. 199–220, 2021. doi: 10.1108/BFJ-04-2020-0293.
[83] A. Tuni and A. Rentizelas, "Improving environmental sustainability in agri-food supply chains: Evidence from an eco-intensity-based method application," *Cleaner Logistics and Supply Chain*, vol. 5, 2022. doi: 10.1016/j.clscn.2022.100081.

[84] V. León-Bravo, F. Caniato, and M. Caridi, “Sustainability assessment in the food supply chain: study of a certified product in Italy,” *Production Planning and Control*, vol. 32, no. 7, pp. 567–584, 2021. doi: 10.1080/09537287.2020.1744761.

[85] N. P. Springer *et al.*, “Sustainable sourcing of global agricultural raw materials: Assessing gaps in key impact and vulnerability issues and indicators,” *PLoS ONE*, vol. 10, no. 6, 2015. doi: 10.1371/journal.pone.0128752.

[86] A. Avadí and P. Fréon, “A set of sustainability performance indicators for seafood: Direct human consumption products from Peruvian anchoveta fisheries and freshwater aquaculture,” *Ecological Indicators*, 2015, doi: 10.1016/j.ecolind.2014.09.006.

[87] Y. Leeben, P. Soni, and G. P. Shivakoti, “Indicators of sustainable development for assessing performance of pineapple canneries: Conceptual framework and application,” *Journal of Food, Agriculture and Environment*, vol. 11, no. 2, pp. 100–109, 2013.

[88] A. Malak-Rawlikowska *et al.*, “Measuring the economic, environmental, and social sustainability of short food supply chains,” *Sustainability (Switzerland)*, vol. 11, no. 15, 2019. doi: 10.3390/su11154004.

[89] M. E. Ruiz Molina, S. Belda-Miquel, A. Hytti, and I. Gil-Saura, “Addressing sustainable food management in hotels: proposing a framework and examining hotel groups,” *British Food Journal*, vol. 124, no. 2, pp. 462–492, 2022. doi: 10.1108/BFJ-12-2020-1171.

[90] S. A. Sarkodie, V. Strezov, H. Weldekidan, E. F. Asamoah, P. A. Owusu, and I. N. Y. Doyi, “Environmental sustainability assessment using dynamic Autoregressive-Distributed Lag simulations—Nexus between greenhouse gas emissions, biomass energy, food and economic growth,” *Science of the Total Environment*, vol. 668, pp. 318–332, 2019. doi: 10.1016/j.scitotenv.2019.02.432.

[91] L. Mastronardi, D. Marino, V. Giaccio, A. Giannelli, M. Palmieri, and G. Mazzocchi, “Analyzing Alternative Food Networks sustainability in Italy: a proposal for an assessment framework,” *Agricultural and Food Economics*, vol. 7, no. 1, 2019. doi: 10.1186/s40100-019-0142-8.

[92] A. Bonanno *et al.*, “Improvement of oxidative status, milk and cheese production, and food sustainability indexes by addition of durum wheat bran to dairy cows’ diet,” *Animals*, vol. 9, no. 9. 2019. doi: 10.3390/ani9090698.

[93] T. Stillitano *et al.*, “An economic sustainability assessment of ‘Fichi di Cosenza’ PDO production compared with other profitable permanent crops,” *Acta Horticulturae*, vol. 2017, no. 1173, pp. 395–400, 2017. doi: 10.17660/ActaHortic.2017.1173.68.

[94] Mariany Costa Deprá, Rosangela Rodrigues Dias, Leila Queiroz Zepka, and Eduardo Jacob-Lopes, “Building cleaner production: How to anchor sustainability in the food production chain?” *Environmental advances*, vol. 9, pp. 100295–100295, Sep. 2022. doi: 10.1016/j.envadv.2022.100295.

[95] S. Schmidheiny, R. Chase, and L. DeSimone, *Signals of change : business progress towards sustainable development*. 1997. Accessed: Jan. 02, 2024. [Online]. Available: https://portals.iucn.org/library/node/22701

[96] G. Halkos and S. Nomikos, “Corporate social responsibility: Trends in global reporting initiative standards,” *Economic Analysis and Policy*, vol. 69, pp. 106–117, Mar. 2021. doi: 10.1016/j.eap.2020.11.008.

[97] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, “An overview of sustainability assessment methodologies,” Apr. 2012, Accessed: Jan. 01, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1470160X11000240

[98] E. Širá, R. Vavrek, I. Kravčáková Vozárová, and R. Kotulič, “Knowledge Economy Indicators and Their Impact on the Sustainable Competitiveness of the EU Countries,” *Sustainability*, vol. 12, no. 10, Art. no. 10, Jan. 2020. doi: 10.3390/su12104172.

[99] D. Meadows, “Indicators and Information Systems for Sustainable Development,” in *The Earthscan Reader in Sustainable Cities*, 1st ed., London: Routledge, 2021, pp. 364–393. doi: 10.4324/9781315800462-21.

[100] S. Damkjaer and R. Taylor, “The measurement of water scarcity: Defining a meaningful indicator,” *Ambio*, vol. 46, no. 5, pp. 513–531, Sep. 2017. doi: 10.1007/s13280-017-0912-z.

[101] A. Warhurst, “Sustainability Indicators and Sustainability Performance Management”.

[102] J. Bebbington, J. Brown, and B. Frame, “Accounting technologies and sustainability assessment models,” *Ecological Economics*, vol. 61, no. 2, pp. 224–236, Mar. 2007. doi: 10.1016/j.ecolecon.2006.10.021.

[103] B. Ness, E. Urbel-Piirsalu, S. Anderberg, and L. Olsson, “Categorising tools for sustainability assessment,” *Ecological Economics*, vol. 60, no. 3, pp. 498–508, Jan. 2007. doi: 10.1016/j.ecolecon.2006.07.023.

[104] “The Product Carbon Footprint Guideline for the Chemical Industry.” Nov. 2022. [Online]. Available: https://www.tfs-initiative.com/

[105] F. Berg, J. F. Kolbel, and R. Rigobon, , “Aggregate Confusion: The Divergence of ESG Rating,” *Review of Finance*, May 2022. doi: 10.1093/rof/rfac033.

[106] "Timeline and History of ESG Investing, Rules and Practices," Sustainability and ESG. Accessed: Jan. 01, 2024. [Online]. Available: https://www.techtarget.com/sustainability/feature/A-timeline-and-history-of-ESG-investing-rules-and-practices
[107] A. Edmans, "The End of ESG." 2023. Accessed: Jan. 01, 2024. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4221990
[108] B. Baue, "ESG or Sustainability: You Choose | Impact Entrepreneur." Accessed: Jan. 01, 2024. [Online]. Available: https://impactentrepreneur.com/esg-or-sustainability-you-choose/
[109] Joanna Krasodomska, E. Zarzycka, and Paweł Zieniuk, "Voluntary sustainability reporting assurance in the European Union before the advent of the corporate sustainability reporting directive: The country and firm-level impact of Sustainable Development Goals," *Sustainable Development*, 2023. doi: 10.1002/sd.2744.
[110] *DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2013/34/EU, Directive 2004/109/EC, Directive 2006/43/EC and Regulation (EU) No 537/2014, as regards corporate sustainability reporting.*
[111] L. Reeder, *Guide to Green Building Rating Systems: Understanding LEED, Green Globes, Energy Star, the National Green Building Standard, and More*, 1st ed. Wiley, 2010. doi: 10.1002/9781118259894.
[112] S. J. Kühne, E. Reijnen, L. Vogt Laasner, and M. Baumgartner, "Can carbon labels encourage green food choices?" *Frontiers in psychology*, vol. 13, Jan. 2023. doi: https://doi.org/10.3389/fpsyg.2022.902869.
[113] M. Li *et al.*, "Global food-miles account for nearly 20% of total food-systems emissions," *Nature food*, doi: 10.1038/s43016-022-00531-w.
[114] F. Sgarbossa and I. Russo, "A proactive model in sustainable food supply chain: Insight from a case study," *International Journal of Production Economics*, 2017. doi: 10.1016/j.ijpe.2016.07.022.
[115] K. C. Krishna Bahadur, I. Haque, A. F. Legwegoh, and E. D. G. Fraser, "Strategies to reduce food loss in the global south," *Sustainability (Switzerland)*, 2016. doi: 10.3390/su8070595.
[116] B. Notarnicola, K. Hayashi, M. A. Curran, and D. Huisingh, "Progress in working towards a more sustainable agri-food industry," *Journal of Cleaner Production*, 2012. doi: 10.1016/j.jclepro.2012.02.007.
[117] J. H. Trienekens, P. M. Wognum, A. J. M. Beulens, and J. G. A. J. Van Der Vorst, "Transparency in complex dynamic food supply chains," *Advanced Engineering Informatics*, vol. 26, no. 1, pp. 55–65, 2012. doi: 10.1016/j.aei.2011.07.007.
[118] J. B. E. M. Steenkamp, "Conceptual model of the quality perception process," *Journal of Business Research*, 1990. doi: 10.1016/0148-2963(90)90019-A.
[119] G. Migliore, G. Schifani, and L. Cembalo, "Opening the black box of food quality in the short supply chain: Effects of conventions of quality on consumer choice," *Food Quality and Preference*, vol. 39, pp. 141–146, 2015. doi: 10.1016/j.foodqual.2014.07.006.
[120] C. Chen, J. Zhang, and T. Delaurentis, "Quality control in food supply chain management: An analytical model and case study of the adulterated milk incident in China," *International Journal of Production Economics*, vol. 152, pp. 188–199, 2014. doi: 10.1016/j.ijpe.2013.12.016.
[121] FAO, "Food wastage footprint," in *Fao, un*, 2013.
[122] B. Lipinski, C. Hanson, J. Lomax, L. Kitinoja, R. Waite, and T. Searchinger, "Reducing food loss and waste. Working paper, installment 2 of creating a sustainable food future," 2016.
[123] C. Willersinn, G. Mack, P. Mouron, A. Keiser, and M. Siegrist, "Quantity and quality of food losses along the Swiss potato supply chain: Stepwise investigation and the influence of quality standards on losses," *Waste Management*, vol. 46, pp. 120–132, 2015. doi: 10.1016/j.wasman.2015.08.033.
[124] B. Devin and C. Richards, "Food waste, power, and corporate social responsibility in the australian food supply chain," *Journal of Business Ethics*, vol. 150, no. 1, pp. 199–210, 2018. doi: 10.1007/s10551-016-3181-z.
[125] A. Patel and D. G. Woodward, "Supermarkets and the organic food supply chain: The potential for waste generation and its mitigation." 2007. doi: 10.1504/IJGENVI.2007.012076.
[126] S. S. Davey and C. Richards, "Supermarkets and private standards: Unintended consequences of the audit ritual," *Agriculture and Human Values*, 2013. doi: 10.1007/s10460-012-9414-6.
[127] C. Richards, H. Bjørkhaug, G. Lawrence, and E. Hickman, "Retailer-driven agricultural restructuring-Australia, the UK and Norway in comparison," *Agriculture and Human Values*, 2013. doi: 10.1007/s10460-012-9408-4.
[128] J. Liu, J. Lundqvist, J. Weinberg, and J. Gustafsson, "Food losses and waste in China and their implication for water and land," *Environmental Science and Technology*, 2013. doi: 10.1021/es401426b.
[129] European Commission and T. Report, "Preparatory study on food waste across EU 27," in *October* 2010.
[130] K. Verghese, H. Lewis, S. Lockrey, and H. Williams, "Packaging's role in minimizing food loss and waste across the supply chain," *Packaging Technology and Science*, 2015. doi: 10.1002/pts.2127.
[131] K. Liljestrand, "Logistics solutions for reducing food waste," *International Journal of Physical Distribution and Logistics Management*, 2017. doi: 10.1108/IJPDLM-03-2016-0085.

[132] J. K. Heising, G. D. H. Claassen, and M. Dekker, "Options for reducing food waste by quality-controlled logistics using intelligent packaging along the supply chain," *Food Additives and Contaminants – Part A Chemistry, Analysis, Control, Exposure and Risk Assessment*, vol. 34, no. 10, pp. 1672–1680, 2017. doi: 10.1080/19440049.2017.1315776.
[133] F. Lomiri and S. Cappello, "Stuffed and starved: The hidden battle for the world food system," *Development*, 2008. doi: 10.1057/dev.2008.63.
[134] D. Gunasekera, "Food production: Cut food waste to help feed world." 2015. doi: 10.1038/524415a.
[135] K. D. Hall, J. Guo, M. Dore, and C. C. Chow, "The progressive increase of food waste in America and its environmental impact," *PLoS ONE*, 2009. doi: 10.1371/journal.pone.0007940.
[136] FAO, "State of Food and Agriculture 2010-2011," 2011.
[137] L. Xue *et al.*, "Missing food, missing data? A critical review of global food losses and food waste data," *Environmental Science and Technology*, 2017. doi: 10.1021/acs.est.7b00401.
[138] "Reducing food's environmental impacts through producers and consumers | Science." Accessed: Jan. 02, 2024. [Online]. Available: https://www.science.org/doi/10.1126/science.aaq0216
[139] C. Cederberg and U. Sonesson, *Global food losses and food waste: extent, causes and prevention; study conducted for the International Congress Save Food! at Interpack 2011, [16–17 May], Düsseldorf, Germany*. Rome: Food and Agriculture Organization of the United Nations, 2011.
[140] T. Wan, D. Wan, L. Wang, Y. Dou, X. Sun, and J. Hu, "Assessment of environmental benefits from phasing out CFCs in refrigerator industry of China," *Beijing Daxue Xuebao (Ziran Kexue Ban)/Acta Scientiarum Naturalium Universitatis Pekinensis*, 2011.
[141] H. Zhao, S. Liu, C. Tian, G. Yan, and D. Wang, "An overview of current status of cold chain in China," *International Journal of Refrigeration*, vol. 88, pp. 483–495, 2018. doi: 10.1016/j.ijrefrig.2018.02.024.
[142] O. I. Aruoma, "The impact of food regulation on the food supply chain," *Toxicology*, 2006. doi: 10.1016/j.tox.2005.12.024.
[143] T. Bosona and G. Gebresenbet, "Food traceability as an integral part of logistics management in food and agricultural supply chain." 2013. doi: 10.1016/j.foodcont.2013.02.004.
[144] M. Vanderroost, P. Ragaert, F. Devlieghere, and B. De Meulenaer, "Intelligent food packaging: The next generation." 2014. doi: 10.1016/j.tifs.2014.06.009.
[145] R. Akkerman, P. Farahani, and M. Grunow, "Quality, safety and sustainability in food distribution: A review of quantitative operations management approaches and challenges," *OR Spectrum*, 2010. doi: 10.1007/s00291-010-0223-2.
[146] M. Soysal, J. M. Bloemhof-Ruwaard, and J. G. A. J. Van Der Vorst, "Modelling food logistics networks with emission considerations: The case of an international beef supply chain," *International Journal of Production Economics*, vol. 152, pp. 57–70, 2014. doi: 10.1016/j.ijpe.2013.12.012.
[147] P. Beske-Janssen, M. P. Johnson, and S. Schaltegger, "20 years of performance measurement in sustainable supply chain management – what has been achieved?" 2015. doi: 10.1108/SCM-06-2015-0216.
[148] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds., *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-56475-3.
[149] R. Kaipia, I. Dukovska-Popovska, and L. Loikkanen, "Creating sustainable fresh food supply chains through waste reduction," *International Journal of Physical Distribution and Logistics Management*, 2013. doi: 10.1108/IJPDLM-11-2011-0200.
[150] R. Manzini and R. Accorsi, "The new conceptual framework for food supply chain assessment," *Journal of Food Engineering*, vol. 115, no. 2, pp. 251–263, 2013. doi: 10.1016/j.jfoodeng.2012.10.026.
[151] M. Fritz and G. Schiefer, "Food chain management for sustainable food system development: A European research Agenda," *Agribusiness*, 2008. doi: 10.1002/agr.20172.
[152] M. Bourlakis, G. Maglaras, D. Gallear, and C. Fotopoulos, "Examining sustainability performance in the supply chain: The case of the Greek dairy sector," *Industrial Marketing Management*, 2014. doi: 10.1016/j.indmarman.2013.08.002.
[153] D. Kumar and Z. Rahman, "Sustainability adoption through buyer supplier relationship across supply chain: A literature review and conceptual framework," *International Strategic Management Review*, 2015, doi: 10.1016/j.ism.2015.04.002.
[154] T. M. Stevens, N. Aarts, C. J. A. M. Termeer, and A. Dewulf, "Social media as a new playing field for the governance of agro-food sustainability." 2016. doi: 10.1016/j.cosust.2015.11.010.
[155] S. K. Mangla, S. Luthra, N. Rich, D. Kumar, N. P. Rana, and Y. K. Dwivedi, "Enablers to implement sustainable initiatives in agri-food supply chains," *International Journal of Production Economics*, vol. 203, no. April 2017, pp. 379–393, 2018. doi: 10.1016/j.ijpe.2018.07.012.
[156] H. Xiaohong Chen, *Approaches to Quantitative Research: A Guide for Dissertation Students: A Guide for Dissertation Students*. Accessed: Jan. 06, 2024. [Online]. Available: https://web-p-ebscohost-com.resursi.rtu.lv/ehost/ebookviewer/ebook/ZTAwMHh3d19fMTAwOTk2M19fQU41?sid=bd3085f2-f73c-4d16-b894-ccf7b684eafe@redis&vid=0&format=EB&rid=1

[157] "SPIRIT 2013 explanation and elaboration: guidance for protocols of clinical trials | The BMJ." Accessed: Jan. 11, 2024. [Online]. Available: https://www.bmj.com/content/346/bmj.e7586
[158] Institute of Medicine (US) Committee on Standards for Systematic Reviews of Comparative Effectiveness Research, *Finding What Works in Health Care: Standards for Systematic Reviews*. Washington (DC): National Academies Press (US), 2011. Accessed: Jan. 11, 2024. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK209518/
[159] H. Buxel, G. Esenduran, and S. Griffin, "Strategic sustainability: Creating business value with life cycle analysis," *Business Horizons*, vol. 58, no. 1, pp. 109–122, Jan. 2015. doi: 10.1016/j.bushor.2014.09.004.
[160] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, and G. Norris, "Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications." Accessed: Dec. 26, 2023. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/15051246/
[161] I. Bartolozzi, F. Rizzi, and M. Frey, "Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy," 2017. doi: 10.1016/j.rser.2017.05.231.
[162] O. Jolliet *et al.*, "IMPACT 2002+: A new life cycle impact assessment methodology." 2003. doi: 10.1007/BF02978505.
[163] S. Humbert, A. D. Schryver, X. Bengoa, M. Margni, and O. Jolliet, "IMPACT 2002 + : User guide," vol. 21, p. 42, 2002.
[164] S. Hellweg, E. Benetto, M. A. J. Huijbregts, F. Verones, and R. Wood, "Life-cycle assessment to guide solutions for the triple planetary crisis," *Nat Rev Earth Environ*, vol. 4, no. 7, Art. no. 7, Jul. 2023. doi: 10.1038/s43017-023-00449-2.
[165] A. Arias, G. Feijoo, and M. T. Moreira, "New Environmental Approach Based on a Combination of Planetary Boundaries and Life Cycle Assessment in the Wood-Based Bioadhesive Market," *ACS Sustainable Chem. Eng.*, vol. 10, no. 34, pp. 11257–11272, Aug. 2022. doi: 10.1021/acssuschemeng.2c03058.
[166] Samuel B. Perez-Vega, "Food processing and value generation align with nutrition and current environmental planetary boundaries," *Sustainable Production and Consumption*, vol. 33, pp. 964–977, Aug. 2022. doi: 10.1016/j.spc.2022.08.022.
[167] European Commission. Joint Research Centre. Institute for Environment and Sustainability., *Evaluation of weighting methods for measuring the EU-27 overall environmental impact.* LU: Publications Office, 2011. Accessed: Jan. 02, 2024. [Online]. Available: https://data.europa.eu/doi/10.2788/88465
[168] X. Bai *et al.*, "Translating Earth system boundaries for cities and businesses," *Nat. Sustain.*, Jan. 2024. doi: 10.1038/s41893-023-01255-w.
[169] V. Martinez-Sanchez, M. A. Kromann, and T. F. Astrup, "Life cycle costing of waste management systems: Overview, calculation principles and case studies," *Waste Management*, vol. 36, pp. 343–355, Feb. 2015. doi: 10.1016/j.wasman.2014.10.033.
[170] A. Ciroth, G. Huppes, W. Klopffer, I. Rudenauer, B. Steen, and T. Swarr, "Environmental life cycle costing," in *SETAC*, D. Hunkeler, K. Lichtenvort, and G. Rebitzer, Eds., New York, 2008.
[171] A. Ciroth, J. Hildenbrand, and B. Steen, "Life Cycle Costing," in *Sustainability Assessment of Renewables-Based Products*, 1st ed., J. Dewulf, S. De Meester, and R. A. F. Alvarenga, Eds., Wiley, 2015, pp. 215–228. doi: 10.1002/9781118933916.ch14.
[172] R. Heijungs, E. Settanni, and J. Guinée, "Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC," *Int. J. Life Cycle Assess.*, vol. 18, no. 9, pp. 1722–1733, Nov. 2013. doi: 10.1007/s11367-012-0461-4.
[173] International Standard Organization, *ISO 14040 International Standard Environmental Management – Life Cycle Assessment – Principles and Framework*, 2006. Accessed: Jan. 06, 2024. [Online]. Available: https://www.iso.org/standard/37456.html
[174] International Standard Organization, *ISO 14044. Environmental management – Life cycle assessment – Requirements and guidelines*, 2006.
[175] T. E. Swarr *et al.*, "Environmental life-cycle costing: a code of practice," *Int J Life Cycle Assess*, vol. 16, no. 5, pp. 389–391, Jun. 2011. doi: 10.1007/s11367-011-0287-5.
[176] F. De Menna, J. Dietershagen, Marion Loubiere, M. Loubiere, Matteo Vittuari, and M. Vittuari, "Life cycle costing of food waste: A review of methodological approaches," *Waste Management*, vol. 73, pp. 1–13, Mar. 2018. doi: 10.1016/j.wasman.2017.12.032.
[177] G. Huppes, M. Van Rooijen, R. Kleijn, A. De Koning, and L. Van Oers, "Report of a project commissioned by the Ministry of VROM-DGM for the RIVM Expertise Centre LCA," Ministry of VROM-DGM, 2004.
[178] G. National and H. Pillars, *Biofuels for a more sustainable future*. 2020.
[179] A. Mazzi, "Introduction. Life cycle thinking," in *Life cycle sustainability assessment for decision-making*, J. Ren and S. Toniolo, Eds., Elsevier Ltd, 2020, pp. 1–4.

[180] L. C. Dreyer, M. Z. Hauschild, and J. Schierbeck, "A framework for social life cycle impact assessment," *International Journal of Life Cycle Assessment*, 2006. doi: 10.1065/lca2005.08.223.

[181] A. Lehmann, D. Russi, A. Bala, M. Finkbeiner, and P. Fullana-i-Palmer, "Integration of social aspects in decision support, based on life cycle thinking," *Sustainability*, 2011. doi: 10.3390/su3040562.

[182] N. Iofrida, A. Strano, G. Gulisano, and A. I. De Luca, "Why social life cycle assessment is struggling in development?" *Int J Life Cycle Assess*, vol. 23, no. 2, pp. 201–203, Feb. 2018. doi: 10.1007/s11367-017-1381-0.

[183] UNEP Setac Life Cycle Initiative, "Guidelines for social life cycle assessment of products and organizations 2020," *Management*, vol. 15, no. 2, 2020, [Online]. Available: http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf

[184] R. Lin, Y. Man, and J. Ren, "Chapter 8 - Framework of life cycle sustainability assessment," in *Life Cycle Sustainability Assessment for Decision-Making*, J. Ren and S. Toniolo, Eds., Elsevier, 2020, pp. 155–173. doi: 10.1016/B978-0-12-818355-7.00008-7.

[185] U. Schenker *et al.*, "Handbook for product social impact assessment. 2020," no. November, 2020. doi: 10.13140/RG.2.2.33455.79523.

[186] International EPD System, *Product Category Rules (PCR) for Social Product Declarations (SPD)*, SPD-PCR 2023:01, Oct. 30, 2023. [Online]. Available: https://www.datocms-assets.com/37502/1698661714-spd-pcr-2023-01-rolling-stock-v1-0-0.pdf

[187] UNEP, One Planet Network, New Earth, and European Commission, "Shout it out: Communicating products' social impacts a white paper of the one planet network consumer information programme," 2018. [Online]. Available: http://www.oneplanetnetwork.org/sites/default/files/white_paper_-_communicating_products_social_impacts_ci-scp_2018.pdf%0Ahttps://www.international-climate-initiative.com/fileadmin/Dokumente/2018/20181023_White_Paper_-_Communicating_Products__Social_Impac

[188] WBCSD, "Sustainable consumption facts and trends from a business perspective," World Business Council for Sustainable Development, 2008. [Online]. Available: https://docs.wbcsd.org/2008/11/SustainableConsumptionFactsAndTrends.pdf

[189] K. Rennert *et al.*, "Comprehensive evidence implies a higher social cost of CO2," *Nature*, vol. 610, no. 7933, pp. 687–692, Oct. 2022. doi: 10.1038/s41586-022-05224-9.

[190] S. Zanoni *et al.*, "Improving Cold Chain Energy Efficiency: EU H2020 project for facilitating energy efficiency improvements in SMEs of the food and beverage cold chains," *Refrigeration Science and Technology*, vol. 2020-August, pp. 361–369, 2020. doi: 10.18462/iir.iccc.2020.292878.

[191] "Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints | International Journal of Precision Engineering and Manufacturing-Green Technology." Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s40684-020-00229-z

[192] Y.-J. Chang, S. Neugebauer, A. Lehmann, R. Scheumann, and M. Finkbeiner, "Life Cycle Sustainability Assessment Approaches for Manufacturing," in *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives*, R. Stark, G. Seliger, and J. Bonvoisin, Eds., in Sustainable Production, Life Cycle Engineering and Management. , Cham: Springer International Publishing, 2017, pp. 221–237. doi: 10.1007/978-3-319-48514-0_14.

[193] P. Ranjan, R. Agrawal, and J. K. Jain, "Life Cycle Assessment in Sustainable Manufacturing: A Review and Further Direction," in *Operations Management and Systems Engineering*, A. Sachdeva, P. Kumar, O. P. Yadav, R. K. Garg, and A. Gupta, Eds., in Lecture Notes on Multidisciplinary Industrial Engineering. Singapore: Springer, 2021, pp. 191–203. doi: 10.1007/978-981-15-6017-0_12.

[194] "Life cycle assessment (LCA) applied to the process industry: a review | The International Journal of Life Cycle Assessment." Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s11367-012-0432-9

[195] M. R. Sabour, H. Zarrabi, and M. Hajbabaie, "A systematic analysis of research trends on the utilization of life cycle assessment in pharmaceutical applications," *Int. J. Environ. Sci. Technol.*, vol. 20, no. 10, pp. 10921–10942, Oct. 2023. doi: 10.1007/s13762-023-05103-4.

[196] A. Fnais *et al.*, "The application of life cycle assessment in buildings: challenges, and directions for future research," *Int. J. Life Cycle Assess.*, vol. 27, no. 5, pp. 627–654, May 2022. doi: 10.1007/s11367-022-02058-5.

[197] A. Zakerhosseini, M. A. Abdoli, S. M. Molayzahedi, and F. K. Salmi, "Life cycle assessment of construction and demolition waste management: a case study of Mashhad, Iran," *Environ Dev Sustain*, Aug. 2023. doi: 10.1007/s10668-023-03703-1.

[198] B. Bayram and K. Greiff, "Life cycle assessment on construction and demolition waste recycling: a systematic review analyzing three important quality aspects," *Int J Life Cycle Assess*, vol. 28, no. 8, pp. 967–989, Aug. 2023. doi: 10.1007/s11367-023-02145-1.

[199] J. G. Backes and M. Traverso, “Social Life Cycle Assessment in the Construction Industry: Systematic Literature Review and Identification of Relevant Social Indicators for Carbon Reinforced Concrete,” *Environ Dev Sustain*, Mar. 2023. doi: 10.1007/s10668-023-03005-6.
[200] M. Kucukvar and O. Tatari, “Towards a triple bottom-line sustainability assessment of the U.S. construction industry,” *Int. J. Life Cycle Assess.*, vol. 18, no. 5, pp. 958–972, Jun. 2013. doi: 10.1007/s11367-013-0545-9.
[201] Ana T. Amorim-Maia *et al.*, “Intersectional climate justice: A conceptual pathway for bridging adaptation planning, transformative action, and social equity,” *Urban Climate*, vol. 41, pp. 101053–101053, Jan. 2022. doi: 10.1016/j.uclim.2021.101053.
[202] Jan Wilkens, Jan Wilkens, Alvine R C Datchoua-Tirvaudey, and Alvine R C Datchoua-Tirvaudey, “Researching climate justice: a decolonial approach to global climate governance,” *International Affairs*, vol. 98, no. 1, pp. 125–143, Jan. 2022. doi: 10.1093/ia/iiab209.
[203] J. Vogel and J. Hickel, “Is green growth happening? An empirical analysis of achieved versus Paris-compliant CO2–GDP decoupling in high-income countries,” *The Lancet Planetary Health*, vol. 7, no. 9, pp. e759–e769, Sep. 2023. doi: 10.1016/S2542-5196(23)00174-2.
[204] Prisca Ugomma Uwaoma, Emmanuel Osamuyimen Eboigbe, Simon Kaggwa, Deborah Idowu Akinwolemiwa, and Stephen Osawaru Eloghosa, “Ecological economics in the age of 4ir: spotlight on sustainability initiatives in the global south,” *International Journal of Advanced Economics*, 2023. doi: 10.51594/ijae.v5i9.647.
[205] G. Enjolras, Magali Aubert, and M. Aubert, “Short food supply chains and the issue of sustainability: a case study of French fruit producers,” Jan. 2018.
[206] S. Lehmann, “Growing Biodiverse Urban Futures: Renaturalization and Rewilding as Strategies to Strengthen Urban Resilience,” *Sustainability*, vol. 13, no. 5, p. 2932, 2021. doi: 10.3390/su13052932.
[207] A. Perino *et al.*, “Rewilding complex ecosystems,” *Science*, vol. 364, no. 6438, Apr. 2019. doi: 10.1126/science.aav5570.
[208] J. Konietzko, “Moving Beyond Carbon Tunnel Vision With A Sustainability Data Strategy,” Forbes. Accessed: Jan. 01, 2024. [Online]. Available: https://www.forbes.com/sites/cognizant/2022/04/07/moving-beyond-carbon-tunnel-vision-with-a-sustainability-data-strategy/
[209] C. Benoit-Norris, “The methodological sheets for sub-categories in social life cycle assessment (S-LCA),” *Pre publication – Version. The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA).*, 2018, doi: 10.1007/978-1-4419-8825-6.
[210] “Systematic literature review on the application of life cycle sustainability assessment in the energy sector | Environment, Development and Sustainability.” Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s10668-021-01559-x
[211] “Bringing nutrition and life cycle assessment together (nutritional LCA): opportunities and risks | The International Journal of Life Cycle Assessment.” Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s11367-021-01982-2
[212] “Life Cycle Assessment for the Agri-Food Sector | SpringerLink.” Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/chapter/10.1007/978-94-007-6116-2_5
[213] “Life cycle-based dashboard for circular agri-food sector | The International Journal of Life Cycle Assessment.” Accessed: Dec. 26, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s11367-022-02118-w
[214] T. Nemecek, N. Jungbluth, L. M. i Canals, and R. Schenck, “Environmental impacts of food consumption and nutrition: where are we and what is next?” *Int. J. Life Cycle Assess.*, vol. 21, no. 5, pp. 607–620, May 2016. doi: 10.1007/s11367-016-1071-3.
[215] F. Diaz *et al.*, “The ICCEE Toolbox. A Holistic Instrument Supporting Energy Efficiency of Cold Food and Beverage Supply Chains,” *Environmental and Climate Technologies*, vol. 26, no. 1, pp. 428–440, Jan. 2022. doi: 10.2478/rtuect-2022-0033.
[216] Statista, “Energy mix in Italy 2018.” 2021. Accessed: Mar. 17, 2021. [Online]. Available: https://www.statista.com/statistics/873552/energy-mix-in-italy/
[217] European Commission, “Facts and figures on the Common Fisheries Policy – Basic statistical data – 2016 Edition,” in *Office of the European Union*, 2016.
[218] L. Proskina, I. Pilvere, A. Nipers, and M. Silovs, “Characteristics of the fishing industry in Latvia,” *19th International Scientific Conference “Economic Science for Rural Development 2018”, Bioeconomy. Finance and Taxes. Home Economics. New Dimensions in the Development of Society*, vol. 49, no. 49, pp. 56–64, 2018. doi: 10.22616/esrd.2018.118.
[219] I. Biuksane and I. Judrupa, “Evaluation of the competitiveness of fisheries sector cluster,” in *Research for rural development*, vol. 2, 2016, pp. 238–245.

[220] Central Statistical Bureau of Latvia, "Fish catch." 2017. Accessed: Feb. 09, 2021. [Online]. Available: http://data1.csb.gov.lv/pxweb/en/lauks/lauks__zvejn__ikgad/?rxid=d8284c56-0641-451c-8b70-b6297b58f464&tablelist=true
[221] I. C. Claussen, E. Indergård, and M. Grinde, "Comparative Life Cycle Assessment (LCA) of production and transport of chilled versus superchilled haddock (Melanogrammus aeglefinus) fillets from Norway to France," *Procedia Food Science*, vol. 1, no. 2211, pp. 1091–1098, 2011. doi: 10.1016/j.profoo.2011.09.163.
[222] H. M. Hoang, T. Brown, E. Indergard, D. Leducq, and G. Alvarez, "Life cycle assessment of salmon cold chains: Comparison between chilling and superchilling technologies," *Journal of Cleaner Production*, 2016. doi: 10.1016/j.jclepro.2016.03.049.
[223] E. S. Hognes, U. Winther, H. Ellingsen, F. Ziegler, A. Emanuelsson, and V. Sund, "Carbon footprint and energy use of Norwegian fisheries and seafood products," *Sustainable Maritime Transportation and Exploitation of Sea Resources*, pp. 1031–1036, 2011. doi: 10.1201/b11810-152.
[224] D. Coley, M. Winter, and M. Howard, "Section 4 food distribution and consumption," in *Sustainable food processing*, John Wiley & Sons, Incorporated, 2013.
[225] L. Matuko, "LIFE CYCLE ASSESSMENT OF COLD SUPPLY CHAINS: A CASE STUDY OF A LATVIAN EGG PRODUCER," Riga Technical University, Riga, Latvia, 2023.
[226] EPD International, *Product Category Rules BIRDS' EGGS IN SHELL, FRESH*, 2011:15. [Online]. Available: https://environdec.com/pcr-library/with-documents
[227] UNFCC, "Nuevo mondoñedo landfill gas recovery, flaring and energy production and transformation for leachate evaporation." 2017. Accessed: Nov. 09, 2021. [Online]. Available: https://cdm.unfccc.int/Projects/DB/ICONTEC1462894251.71/view
[228] J. Yliopisto, "Evaluation of potential technologies and operational scales reflecting market needs for low-cost gas upgrading systems. VALORGAS: Valorisation of food waste to biogas," 2013.
[229] E. Ryckebosch, M. Drouillon, and H. Vervaeren, "Techniques for transformation of biogas to biomethane," *Biomass and Bioenergy*, vol. 35, no. 5, pp. 1633–1645, 2011. doi: 10.1016/j.biombioe.2011.02.033.
[230] F. Bauer, C. Hulteberg, T. Persson, and D. Tamm, "Biogas upgrading – Review of commercial technologies," 2013.
[231] W. Stumm and J. J. Morgan, *Aquatic chemistry: chemical equilibria and rates in natural waters*, 3rd Edition. New York: Wiley, 1996.
[232] S. S. J. Hullu, J. Maassen, "Comparing different biogas upgrading techniques," 2008.
[233] A. Bejan, "Economies of scale," in *Freedom and evolution: Hierarchy in nature, society and science*, Cham: Springer International Publishing, 2020, pp. 13–20. doi: 10.1007/978-3-030-34009-4_2.
[234] M. A. Ruiz Restrepo, "Bioenergía, una alternativa energética sustentable para Colombia. Aplicación del Concepto Integrado de Sostenibilidad (ICoS)," 2019, Accessed: Jan. 11, 2024. [Online]. Available: https://repositorio.unal.edu.co/handle/unal/76373
[235] Simapro manual PRe Consultants, "Introduction to LCA with SimaPro 7," *PRé Consultants, the Netherlands. Version*, no. October, pp. 1–88, 2008.
[236] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *The International Journal of Life Cycle Assessment*, vol. 21, no. 9, pp. 1218–1230, 2016. doi: 10.1007/s11367-016-1087-8.
[237] IPCC, "Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change," IPCC, Cambridge, 2013. [Online]. Available: https://www.ipcc.ch/report/ar5/wg1/
[238] "A framework for energy use indicators and their reporting in life cycle assessment - Arvidsson - 2016 - Integrated Environmental Assessment and Management – Wiley Online Library." Accessed: Jan. 06, 2024. [Online]. Available: https://setac.onlinelibrary.wiley.com/doi/10.1002/ieam.1735
[239] M. A. J. Huijbregts *et al.*, "Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?" *Environ. Sci. Technol.*, vol. 40, no. 3, pp. 641–648, Feb. 2006. doi: 10.1021/es051689g.
[240] A. M. Boulay *et al.*, "The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE)," *The International Journal of Life Cycle Assessment*, vol. 23, no. 2, 2017. doi: 10.1007/s11367-017-1333-8.

Fabian Andres Diaz Sanchez was born in Colombia and holds a degree in Chemical Engineering from Universidad de America in Colombia. After 10 years working in the chemical, oil, and gas sector, he moved to Latvia, where he obtained his Master's in Environmental Science with a certificate of excellence from Riga Technical University (2019), focusing on life cycle assessment. Afterwards, he was a researcher at RTU, combining his job with his PhD studies. He is currently working on life cycle sustainability assessment for different industrial sectors, supporting the construction industry on LCA scalability and automation towards environmental product declarations, digital declaration of performance, and digital product passports.