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Review Article

Reviewing the Multi-Sectoral Application of Life Cycle Assessment (LCA) for Environmental Impact Evaluation and Integration with Socio-Economic Analysis for Sustainable Practices

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Abstract
This review analyzes the application of LCA in assessing the environmental effects of products, processes, and services in different industries. The study utilizes academic databases and hand-picked papers from 24 countries to examine recent advancements in LCA applications during the past two decades. The objective is to identify prospects for enhancing LCA methodologies and improving environmental impact assessments in diverse sectors and geographic regions. The LCA method is subject to limitations, one of which is its failure to consider socioeconomic factors. In order to tackle these issues, it is necessary to employ additional approaches, such as the Regional Sustainability Assessment Methodology. In order to enhance project management in the construction sector, combining LCA with Building Information Modeling is beneficial. On the other hand, dynamic modeling techniques and quantitative microbial risk assessment are necessary in agriculture. The Packaging Impact Quick Evaluation Tool assists in the decision-making process for food packaging development while integrating LCA with GIS in transportation enhances accuracy and precision. Researchers can assess shipping operations' environmental impact and energy efficiency by integrating LCA with the Energy Efficiency Design Index and Energy Efficiency Operation Index.

Key Words
Life Cycle Assessment (LCA), Sustainability, LCA applications, LCA limitations, LCA development, Geographic Information Systems (GIS)

Çok Sektörlü Yaşam Döngüsü Değerlendirmesi (YDD) Uygulamalarının Çevresel Etki Değerlendirmesi ve Sosyo-Ekonomik Analiz ile Entegrasyonu Üzerine Bir İnceleme: Sürdürülebilir Uygulamaların Değerlendirilmesi

Öz
Bu inceleme, YDD uygulamasının farklı sektörlerdeki ürünlerin, süreçlerin ve hizmetlerin çevresel etkilerini değerlendirmede kullanımını analiz ediyor. Çalışma, son yirmi yıldaki YDD uygulamalarındaki son gelişmeleri incelemek için 24 ülkeden akademik veri tabanlarını ve özenle seçilmiş makaleleri kullanıyor. Amaç, YDD metodolojilerini geliştirmek ve farklı sektörlerde ve coğrafi bölgelerde çevresel etki değerlendirmelerini iyileştirmek için potansiyelleri belirlemektir. YDD yöntemi, sosyo-ekonomik faktörleri hesaba katmaması gibi kısıtlamalara sahiptir. Bu sorunları ele almak için, Bölgesel Sürdürülebilirlik Değerlendirme Metodolojisi gibi ek yaklaşımlar kullanmak gerekir. İnşaat sektöründe proje yönetimini geliştirmek için, YDD'yı Bina Bilgi Modellemesi ile birleştirmek faydalıdır. Öte yandan tarımda dinamik modelleme teknikleri ve kantitatif mikrobiyal risk değerlendirmesi gereklidir. Gıda ambalajı geliştirme sürecinde karar verme sürecine yardımcı olan Ambalaj Etkisi Hızlı Değerlendirme Aracı, YDD'yı Ulaştırmada Coğrafi Bilgi Sistemleri (CBS) ile entegre etmek ise doğruluk ve hassasiyeti artırır. Araştırmacılar, YDD'yı Enerji Verimliliği Tasarım Endeksi ve Enerji Verimliliği İşletme Endeksi ile entegre ederek deniz taşımacılığının çevresel etkisini ve enerji verimliliğini değerlendirebilirler.

Anahtar Kelimeler
Yaşam Döngüsü Değerlendirmesi (YDD), Sürdürülebilirlik, YDD uygulamaları, YDD kısıtlamaları, YDD gelişimi, Coğrafi Bilgi Sistemleri (CBS)

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1. Introduction

1.1. Life Cycle Assessment (LCA) Overview

Assessing the environmental impacts of products, processes, and services, whether the impacts are direct or indirect, is crucial. The Life Cycle Assessment (LCA) methodology is essential for evaluating the environmental impact. LCA offers a thorough assessment that is highly appealing. It evaluates the environmental impact of products, processes, and services throughout their entire lifecycle, from extraction to disposal. The LCA results provide valuable insights into the environmental impact of products, processes, and services. Understanding and acknowledging the benefits and limitations of the LCA tool are crucial aspects of sustainability efforts and informed decision-making for a more environmentally aware future. The comprehensive nature of LCA arises from its consideration of various crucial environmental factors, such as resource consumption, energy usage, air and water pollution, soil degradation, and overall environmental deterioration. This comprehensive approach provides a holistic perspective, enabling stakeholders to recognize opportunities for environmental enhancement and make well-informed choices regarding product development and resource management. Curran (2013) highlights the importance of the LCA methodology in evaluating the environmental impact of products and processes. This methodology is closely aligned with the core objective of sustainability evaluation. This emphasis underscores the significance of LCA in advocating for sustainable practices and directing decision-making towards solutions that are more ecologically sound. Although LCA frequently evaluates the environmental effects of products or processes, it might not fully tackle the broader sustainability factors linked to economic and social aspects (Maier et al., 2016; Padilla-Rivera et al., 2019; Nikolić et al., 2019; Mahmood et al., 2018). These sources assert that LCA primarily emphasizes environmental impacts while occasionally overlooking the social and economic dimensions of sustainability. Maier et al. (2016), Padilla-Rivera et al. (2019), Nikolić et al. (2019), and Mahmood et al. (2018) suggest utilizing alternative methodologies or approaches to assess social and economic impacts. They acknowledge the importance of LCA in evaluating environmental effects. However, previous studies did not adequately explain how the benefits and applications of LCA could serve as the foundation for its development in various sectors.

The LCA method evaluates various materials, highlighting the adaptability of this approach in appraising a wide range of products and materials, with a particular emphasis on their environmental attributes. An important deficiency identified in the literature is the requirement for a more extensive framework that connects life cycle sustainability inquiries to the necessary knowledge for addressing them (Guinée et al., 2010). There is a significant lack of research regarding the sensitivity of LCA modeling choices, specifically when it comes to evaluating the environmental impacts of buildings (Häfliger et al., 2017). Moreover, the absence of a uniform approach for carrying out life cycle sustainability assessments presents a notable obstacle in contemporary LCA research (Nikolić et al., 2019). Moreover, the absence of comprehensive protocols for carrying out LCA studies in particular sectors, such as the geothermal industry, obstructs the ability to compare outcomes and restricts the efficacy of environmental evaluations (Parisi et al., 2020). LCA is an essential tool used to assess the environmental consequences of products, processes, and services. Although LCA provides a thorough evaluation of environmental impacts, it frequently neglects considerations of social and economic sustainability. This study seeks to fill this void by examining the practicability of integrating social and economic factors into current LCA frameworks.

The current research on LCA also emphasizes the necessity of adopting a more cohesive approach and enhancing data collection methods in particular sectors. This study examines the utilization of LCA in eight crucial sectors and highlights opportunities for enhancement, specifically concerning data sensitivity and the absence of standardized protocols in sectors such as geothermal energy.

This research aims to improve the comprehensiveness and applicability of LCA by analyzing and addressing its limitations. We aim to enhance the development of a comprehensive LCA framework that incorporates social, economic, and environmental factors, with the ultimate objective of fostering sustainable decision-making in diverse industries.

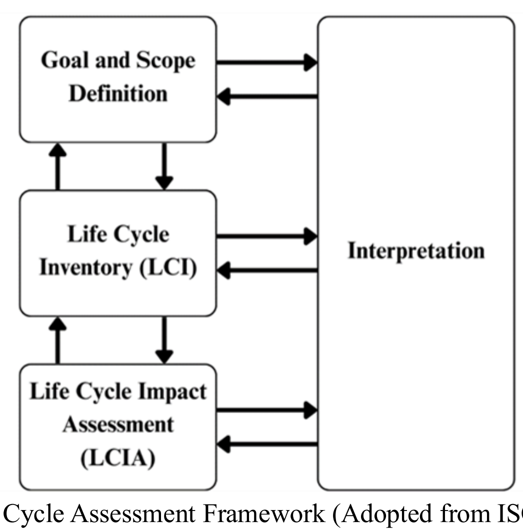

Figure 1. Life Cycle Assessment Framework (Adopted from ISO 14040:2006).

1.2. LCA Framework

The LCA methodology has undergone substantial development to thoroughly assess environmental impacts across diverse sectors. In the 1970s, LCA primarily concentrated on energy analysis. However, it has evolved into a comprehensive assessment of environmental burdens over time (Guinée et al., 2010). Figure 1 illustrates the LCA methodology, which consists of four main steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO 14040:2006; Diyarma et al., 2019).

1.2.1. Goal and scope definition

Prior to conducting an assessment, it is crucial to ascertain the objectives, limitations, and intended applications of the assessment. The definition of goal and scope is the initial and crucial stage that establishes the foundation for a meticulously designed LCA study (ISO 14040:2006). This stage encompasses the identification of the functional unit, the establishment of system boundaries, and the selection of impact categories for evaluation. In order to conduct a thorough assessment, it is essential to establish the parameters for evaluating the various stages of the life cycle, which include production, distribution, use, and disposal (ISO 14040:2006).

During the goal and scope definition phase, it is imperative to establish a process for quality assurance in order to guarantee the dependability and uniformity of the evaluation (Kłos, 2002). In order to conduct the assessment, it is necessary to determine the origins of the data, the methodologies to be employed, and the assumptions to be made. Additionally, it is important to recognize any limitations or uncertainties in the analysis (Finnveden et al., 2009). Multiple scenarios can be contemplated to accommodate fluctuations and uncertainties in technology and the environment. The initial stage of the LCA, as described by Fuc et al. (2016), establishes the limits and objectives of the assessment, providing a definitive plan for subsequent stages, including the life cycle inventory analysis, life cycle impact assessment, and interpretation.

1.2.2. Life cycle inventory (LCI) analysis

The LCI encompasses a comprehensive gathering of data on all the inputs and outputs associated with a product or process. The collected data encompasses the entire life cycle of a product, from the extraction of raw materials to its production, usage, and disposal stages, as defined by the ISO 14040:2006 standard. The significance of this step has been underscored by multiple studies (Diyarma et al., 2019; Chandra et al., 2018; Pons et al., 2018). LCI is the process of methodically measuring and gathering data. This thorough approach includes evaluating the amount of energy used, the materials used, and the resulting outputs throughout the entire lifespan of a product (Pons et al., 2018; Curran, 2013). LCI enables the assessment of environmental performance among different options. This step is crucial for identifying important environmental areas of concern and the processes that have the greatest impact (Mohd Azman et al., 2021). LCI has gained widespread use due to the availability of software tools like OpenLCA, GaBi, and SimaPro. These tools assist in assessing the environmental impacts of various industrial processes.

When comparing these software tools, Open LCA stands out for its user-friendly interface and accessibility to databases like ecoinvent, making it suitable for conducting LCA analyses in a straightforward manner (Pons et al., 2018). Gabi, on the other hand, is known for its comprehensive databases and detailed LCI analysis capabilities, making it ideal for in-depth assessments across different sectors (Pero et al., 2023). SimaPro excels in offering a wide range of impact assessment methods, allowing for a thorough evaluation of environmental impacts in complex systems (Fuć et al., 2016). Overall, The choice of software would depend on the specific requirements of the LCA study and the complexity of the system being analyzed.

1.2.3. Life cycle impact assessment (LCIA)

After finishing the LCI phase, the focus shifts to the life cycle impact assessment (LCIA) phase, which is described in detail by Suryawan et al. (2020) and Acero et al. (2015). During this stage, the product or service's potential environmental impacts are methodically categorized, described, and evaluated for their importance (Young et al., 2021). This crucial phase efficiently converts numerical LCI data into descriptive indicators that express the environmental impact of the product or service across various categories of influence, as defined by the International Organization for Standardization (ISO 14040:2006). The LCIA methodology involves the analysis of various factors, such as resource use, emissions, and their potential impacts on human health, the natural ecosystem, and resource depletion. The evaluation thoroughly assesses the effects in various areas, including global warming, acidification, eutrophication, human toxicity, and resource depletion. Table 1 provides a concise overview of the commonly used impact categories. It is essential to utilize LCIA methods in order to gain a thorough understanding of the environmental consequences of products and services. These methods assess the impacts of resource utilization and emissions across the entire life cycle of a product or service, encompassing activities from the extraction of raw materials to the disposal of waste. It is crucial to take into account the impact assessment categories of these methods. Table 2 displays the LCIA methods, as well as the corresponding impact categories available for each method.

1.2.4. The interpretation

The interpretation stage facilitates well-informed decision-making. It adheres to sustainability principles by pinpointing environmental hotspots and areas for potential enhancement across the product's entire lifespan, encompassing production, usage, and disposal (Hertwich, 2005). It is possible to come to conclusions and make suggestions for improving environmental performance by carefully looking at and making sense of the LCA results from the inventory and impact assessment stages (Palousis et al., 2008). A thorough comprehension of environmental consequences enables the comparison of various products or services, ultimately facilitating the selection of more sustainable alternatives (Flipse, 2014).

Table 1. Short Description of The Most Used Environmental Impact Categories (Acero et al., 2015).

Impact Category	Explanation	Indicator	Damage (Endpoint) Categories
Acidification	The decrease in pH caused by the acidifying impact of human-made emissions	Rise in the acidity levels in water and soil systems	Ecological degradation and biodiversity loss
Climate change	Global temperature change resulting from the presence of greenhouse gases	Disruptions in worldwide temperature and climatic occurrences	- The overall decline in biodiversity, including crops, forests, coral reefs, and other ecosystems. - Thermal fluctuations -Anomalous climatic phenomena, such as intensified cyclones and heavy storms.
Depletion of abiotic resources	The decline in the accessibility of non-biological resources (both non-renewable and renewable) due to their unsustainable utilization.	Diminution of resources.	Destruction of natural resources and potential collapse of the ecosystem
Ecotoxicity	The detrimental impacts of chemicals on an ecosystem.	The decline in biodiversity and the disappearance of species.	Destruction of the ecosystem and extinction of species.
Eutrophication	Nutrient accumulation in aquatic ecosystems.	-Elevated levels of nitrogen and phosphorus concentrations - Production of organic matter through the growth and accumulation of biomass, such as algae.	Ecological degradation.
Human toxicity	Adverse impacts of chemical substances on human health.	The health risks associated with ionizing radiation include cancer, respiratory diseases, and other non-carcinogenic effects.	Health of the human body.
Ionising radiation	Ionizing radiation consists of particles with sufficient energy to free an electron from an atom or molecule.	Consequences of radiation exposure include deteriorating health, increased risk of cancer, and various illnesses.	Impact of human well-being on the quality of ecosystems.
Land use	The effects on the land resulting from agriculture, human settlement, and the extraction of resources.	Loss of biodiversity, erosion of soil, quantity of organic matter, etc.	Depletion of natural resources, both non-renewable and renewable.
Ozone layer depletion	The stratospheric ozone layer is being reduced as a result of human activities that release ozone depleting substances.	The rising in ultraviolet UV-B radiation has led to an increase in the number of cases of skin illnesses.	The interrelationship between human health and the quality of ecosystems.
Particulate matter	These are minute particles that are suspended in the air and are produced by human activities such as burning and extracting resources.	There is an elevation in the concentration of various particles of different sizes that are suspended in the air, specifically particles with diameters of PM10, PM2.5, and PM0.1.	Health of the human body.
Photochemical oxidation	Photochemical smog is formed as a result of the interaction between sunlight, heat, and the emissions of non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx).	Rise in the occurrence of summer smog.	The interplay between human health and the quality of ecosystems.

Table 2. The presence of impact categories in method (✓)means that those categories are included in that method, while any categories not included are represented by (–) (Acero et al., 2015).

Methods	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy use	Eutrophication	Human toxicity
CML (baseline)	✓	✓	✓	✓	–	✓	✓
CML (non-baseline)	✓	✓	✓	✓	–	✓	✓
Cumulative Energy Demand	–	–	–	–	✓	–	–
Eco-indicator 99 (E)	✓	✓	✓	✓	–	✓	✓
Eco-indicator 99 (H)	✓	✓	✓	✓	–	✓	✓
Eco-indicator 99 (I)	✓	✓	✓	✓	–	✓	✓
Eco-Scarcity 2006	–	–	✓	–	–	–	–
ILCD 2011, endpoint	✓	✓	–	–	–	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	–	✓	✓
TRACI 2.1	✓	✓	✓	✓	–	✓	✓
USEtox	–	–	–	✓	–	–	✓

Table 2 (Continued). The presence of impact categories in method (✓)means that those categories are included in that method, while any categories not included are represented by (–) (Acero et al., 2015).

Method	Ionising Radiation	Land use	Odor	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	–	–	–	✓	–	✓
CML (non-baseline)	✓	✓	✓	✓	–	✓
Cumulative Energy Demand	–	–	–	–	–	–
Eco-indicator 99 (E)	✓	✓	–	✓	✓	–
Eco-indicator 99 (H)	✓	✓	–	✓	✓	–
Eco-indicator 99 (I)	✓	✓	–	✓	✓	–
Eco-Scarcity 2006	–	–	–	–	–	–
ILCD 2011, endpoint	✓	✓	–	✓	✓	✓
ILCD 2011, midpoint	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	–	✓	✓	✓
TRACI 2.1	–	–	–	✓	✓	✓
USEtox	–	–	–	–	–	–

2. Methodology

2.1. Objectives

The objective of this study was to examine the present applications of LCA methodology across various industries. The objective is to enhance the understanding of decision-makers, designers, and practitioners in diverse domains regarding the significance of employing LCA for the sustainable and responsible governance of human activities. This measure will aid in safeguarding human well-being, preserving natural resources, and preserving the overall health of the planet.

2.2. Search Strategy

The academic databases ScienceDirect, Scopus, and Web of Science were used to conduct a literature search on environmental impact assessment. The search strategy utilized the term LCA along with relevant sectors for environmental impact assessment and corresponding keywords for each sector. The sectors encompassed in the study are construction, wastewater treatment, agriculture, waste management, manufacturing, energy, packaging, and transportation. By combining these search terms, the search yielded a comprehensive collection of relevant literature on the environmental impact assessment of various sectors.

2.3. Geographical Scope

The selected papers spanned a broad geographical area, involving research conducted in 24 countries: Australia, Brazil, Canada, China, England, France, Germany, Greece, India, Indonesia, Iran, Italy, Japan, Lithuania, Poland, Portugal, Saudi Arabia, South Korea, Spain, Sweden, Switzerland, Turkey, the United States, and Vietnam.

2.4. Inclusion Criteria

The study's inclusion criteria mandated that the research must have been published between 2005 and 2024 and be written in English. This focus was to concentrate on the most recent developments in LCA applications over the last two decades. A total of 51 scientific papers (comprising 49 research articles and 2 reports) were selected for review. The study prioritized research that showcased the utilization of the LCA methodology in evaluating environmental impacts. The selected papers were categorized into different sectors, with specific keywords used to filter the search:

- Construction (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, Construction materials, concrete, Environmental Impact, Environmental Impact Assessment.
- Wastewater Treatment (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, wastewater treatment, Wastewater, Environmental impact, Environmental impact assessment, Life cycle analysis.
- Agriculture (5 scientific papers): LCA, Life Cycle Assessment, Environmental sustainability, Environmental impact, Environmental impact assessment, Agriculture, Agri-food.
- Waste Management (10 scientific papers): LCA, Life Cycle Assessment, Environmental impact, Environmental impact assessment, Waste management, Recycling, Landfill, incineration.
- Manufacturing (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, Carbon footprint, circular economy, supply chain, manufacturing.
- Energy (5 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, energy transition, renewable energy, electricity, heat, energy.
- Packaging (4 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, sustainable packaging, packaging, green packaging.
- Transportation (6 scientific papers): Life Cycle Assessment, LCA, Sustainability, Transportation, Environmental impact, Environmental impact assessment, Greenhouse Gas Emissions.

2.5. Analytical Methods

The emphasis was on studies that demonstrated the practical application of Life Cycle Assessment (LCA) in combination with other models to evaluate environmental impacts, while presenting the primary findings of each study. The objective of this approach is to identify opportunities for enhancing LCA methodologies and improving environmental impact assessments in various sectors and geographic areas.

3. Results

The significance of LCA in environmental management has steadily grown. It provides a method for organizations to assess the environmental impact of a product or service throughout its entire life cycle (Kłos, 2002). The versatility of this technology is evident in its successful adoption in a variety of industries, as shown in Table 3 and discussed in this article.

Table 3. Multi-Sectoral Studies Used LCA Last Two Decades.

Sector	Authors(s) and Year	Country
Construction	Kawai et al. (2005)	Japan
	Hossaini et al. (2014)	Canada
	Kim et al. (2016)	South Korea
	Häfliger et al. (2017)	Switzerland
	Mohammadi & South (2017)	Australia
	Gomes et al. (2019)	Brazil
	Ayagapin & Praene (2020)	France
Wastewater Treatment	Gaterell et al. (2005)	England
	Machado et al. (2007)	Portugal
	Harder et al. (2014)	Sweden
	Risch et al. (2015)	France
	Pretel et al. (2016)	Spain
	Lam et al. (2022)	China
	Rawindran et al. (2024)	Saudi Arabia
Agriculture	Russo and Mugnozza (2005)	Italy
	Bevilacqua et al. (2007)	Italy
	Yang and Suh (2015)	United States
	Turolla et al. (2020)	Italy
	Lulovicova and Bouissou (2024)	France
Waste Management	Lundie & Peters (2005)	United States
	Miliūte & Staniškis (2009)	Lithuania
	Ali et al. (2016)	China
	Corrado et al. (2017)	Italy
	Grzesik (2017)	Poland
	Omid et al. (2017)	Iran
	Haupt et al. (2018)	Switzerland
	Wang et al. (2020)	England
	Garbounis et al. (2022)	Greece
	Avarand et al. (2023)	Iran

Table 3 (Continued). Multi-Sectoral Studies Used LCA Last Two Decades.

Manufacturing	Malmodin et al. (2010)	Sweden
	Cheah et al. (2013)	United States
	Bunnak et al. (2016)	England
	Egilmez et al. (2017)	United States
	Malmodin & Lundén (2018)	Sweden
	Amato et al. (2021)	Italy
	Schoeneberger (2024)	United States
Energy	Malmodin et al. (2010)	Sweden
	Baumgärtner et al. (2021)	Switzerland
	Parisi et al. (2020)	Italy
	Reinert et al. (2022)	Germany
	Wang et al. (2024)	China
Packaging	Bovea et al. (2005)	Spain
	Cappiello et al. (2021)	Germany
	Laso et al. (2017)	Spain
	Molina-Besch & Pålsson (2015)	Sweden
Transportation	Samaras & Meisterling (2008)	Pennsylvania
	Ongel (2015)	Turkey
	Sopha et al. (2016)	Indonesia
	Folęga & Burchart-Korol (2017)	Poland
	Quang et al. (2021)	Vietnam
	Del Pero et al. (2023)	Italy

3.1. Construction

Several studies and articles conducted between 2005 and 2023 seek to measure the ecological consequences of buildings and construction activities using a LCA, as shown in Table 3. The environmental impact of concrete production is a pressing concern. Studies by Kawai et al. (2005) revealed that concrete is responsible for a significant portion of CO_2 emissions, even exceeding steel. Kim et al. (2016) investigated ways to mitigate this impact. Their findings suggest that high-strength concrete can achieve a reduction of 10% to 25% in various environmental impact categories compared to normal strength concrete. However, Häfliger et al. (2017) point out the complexities involved in Life Cycle Assessments (LCA) of buildings. Their research using the Ecoinvent v2.2 database highlights that modeling choices can significantly influence the results, particularly regarding the replacement phase of building materials.

Further research by Mohammadi and South (2017) reinforces the significant influence of cement on concrete's environmental impact. They found the Global Warming Potential (GWP) of concrete products varied considerably, and suggested that using alternative materials or cement with higher mineral additives could be a solution. Their study also identified potential local consequences like acidification and eutrophication. Gomes et al. (2019) offered a promising solution – geopolymer concrete. Their LCA methodology demonstrated a 43% reduction in carbon emissions compared to traditional Portland cement concrete, indicating its potential to address climate change concerns. While Ayagapin & Praene (2020) observed a 37% increase in the Global Warming Potential for construction on Reunion Island, this might be due to the specificities of the project (218 kg-CO_2eq/m^2 of constructed area).

These studies highlight the substantial environmental impact of concrete production but also offer promising avenues for mitigation through the use of high-strength concrete, alternative materials, and geopolymer concrete. On the other hand, in developing the LCA framework, Hossaini et al. (2014) attempted to introduce a comprehensive framework that combines Analytic Hierarchy Process (AHP) with Life Cycle Sustainability Assessment (LCSA) for buildings. The framework is exemplified by a case study of mid-rise structures made of wood and concrete frames in Vancouver, BC, Canada. The findings indicate that the environmental efficiency of buildings in Canada is primarily influenced by the energy consumed over the lifespan of the building, rather than the choice of structural materials. Enhancing the environmental efficiency of buildings can encourage the implementation of low carbon building design using various structural systems. The framework can be utilized for future decision-making in selecting sustainable alternatives in the construction sector, taking into account not only environmental factors but also social and economic factors. Nevertheless, the authors encountered difficulties and constraints in the AHP-based LCSA model, including the presence of confusion and redundancy among various criteria.

3.2. Wastewater Treatment

LCA studies, as shown in Table 3, have thoroughly examined wastewater treatment to assess its environmental effects and investigate different approaches, such as pathogen hazard control. Risch et al. (2015) conducted a comparative analysis that proposed a comprehensive LCA of urban wastewater systems (UWS), which encompasses the construction and operation of sewer systems and wastewater treatment plants (WWTPs). A study revealed that the development of sewer infrastructure has a greater environmental impact than the construction and operation of wastewater treatment plants (WWTPs). The construction phase is the main factor driving this impact in various categories. Gaterell et al. (2005) conducted a study using LCA methodologies to evaluate the environmental effects associated with sewage treatment procedures. They suggested that reducing the energy needed for operations and minimizing the use of synthetic materials for bio-mass growth would enhance environmental performance. In a similar vein, Harder et al. (2014) examined how to incorporate pathogen hazards into LCA by utilizing quantitative microbial risk assessment. Their focus was on the impact on human health, and they estimated that the total risk from pathogens ranged from 0.2 to 9 disability-adjusted life years (DALY) per year of operation for a simulated wastewater treatment system serving 28,600 individuals.

In their study, Machado et al. (2007) employed LCA to evaluate and compare various wastewater treatment techniques suitable for small, decentralized rural communities. The researchers assessed energy-efficient systems, namely the constructed wetland and slow rate infiltration, in comparison to conventional systems such as the activated sludge process. The study emphasized that energy-saving systems have a negligible environmental impact, especially with regards to global warming. Strategies employed to reduce the environmental impact throughout the life cycle included careful selection of construction materials and prolonging the operational lifespan of systems. These measures led to a significant decrease in both CO_2 emissions and abiotic resource depletion. By increasing the operational lifespan of constructed wetland and slow rate infiltration systems by 10%, there was a corresponding decrease of 1% in CO_2 emissions and a 7% reduction in abiotic depletion. Moreover, the replacement of steel with HDPE in activated sludge tanks resulted in a 1% reduction in CO_2 emissions and a 5% decrease in abiotic depletion indicator. Pretel et al. (2016) performed a comprehensive analysis that compared anaerobic membrane bioreactors with aerobic urban wastewater treatment technologies. The study revealed that the anaerobic system, especially when combined with chemical-assisted sedimentation post-treatment, is both environmentally sustainable and economically feasible. It provides significant reductions in global warming potential, marine aquatic ecotoxicity, abiotic depletion, and acidification. Additionally, this system has an impressively low energy consumption of 0.04 kWh per cubic meter and generates minimal sludge. Furthermore, it offers lower life cycle costs, with a minimum value of approximately V0.135 per m^3, when compared to alternative urban wastewater treatment methods.

Subsequent research concentrated on particular advancements and their ecological consequences. Lam et al. (2022) evaluated the ecological impacts of utilizing phosphorus products obtained from wastewater in agricultural systems, employing six distinct recovery techniques. Their research demonstrated substantial advantages in terms of decreased global warming potential, eutrophication, ecotoxicity, and acidification. This underscores the significance of taking into account the long-term consequences and user viewpoints in circular economy practices. In addition, Rawindran et al. (2024) investigated the environmental consequences of employing an integrated membrane bioreactor for the treatment of microalgal wastewater. Their research revealed a significant 63% decrease in the environmental impact in various areas, including freshwater ecotoxicity, eutrophication, and marine ecotoxicity. This highlights the potential benefits of reusing treated wastewater.

3.2. Agriculture

Numerous studies in the agricultural sector have investigated the environmental consequences of agricultural practices. These studies have employed LCA to assess the impact of these practices. Table 3 displays a selection of these studies, which emphasize the significance of employing LCA to attain sustainable agricultural management practices and reduce environmental impacts. In 2005, Russo and Mugnozza conducted a LCA study on greenhouse agriculture in West European territory, comparing the environmental compatibility of horticultural production in different greenhouse typologies. Results show varying environmental impacts for different greenhouse structures, with steel and glass greenhouses having the highest emissions, while wood greenhouses are the most eco-compatible. The study evaluates hydroponic versus soil cultivation, highlighting higher environmental indexes for hydroponic systems due to increased energy consumption and gas emissions.

Bevilacqua et al. (2007) conducted an analysis of the impact assessment results of the entire life cycle of pasta. The effects encompass carcinogens, respiratory organics, climate change, ecotoxicity, acidification, and fossil fuel consumption. The pasta life cycle has the greatest influence on the quality of the ecosystem, particularly in terms of ecotoxicity and acidification. It also significantly contributes to the depletion of nonrenewable resources, specifically minerals and fossil fuels. In a study conducted by Yang and Suh (2015), it was discovered that the ecological health of freshwater systems experienced a 50% decrease in impact per hectare of corn and cotton between 2000-2010. The freshwater ecotoxicity impacts of corn and cotton have decreased due to changes in pesticide usage, primarily due to the widespread adoption of genetically modified crops. The primary cause of this shift is primarily attributed to the cultivation of genetically modified (GM) crops, which have decreased the use of insecticides and relatively harmful herbicides like atrazine. Conversely, soybeans' freshwater ecotoxicity impact has notably escalated due to the proliferation of an invasive species, resulting in an upsurge in the utilization of insecticides.

Turolla et al. (2020) utilized LCA to assess the ecological sustainability of Manila clam farming in aquaculture, taking into account various impact categories. The findings indicate that area preparation, fuel combustion, and plastic bags were the primary factors responsible for the environmental impacts. The carbon sequestration potential of 1 ton of clams has been quantified, along with its ability to reduce eutrophication by fixing nitrogen and phosphorous in shells. This results in a net carbon capture of 444.55 kg, 1.54 kg of N, and 0.31 kg of P annually. In their study, Lulovicova and Bouissou (2024) conducted a prospective investigation to pinpoint regions in the agricultural industry of Finistere, France that have a significant environmental footprint. They employed metrics such as the consequences of climate change and the limited availability of fossil resources. The results indicate that the main environmental areas of concern in the examined local food system originate from indirect factors, such as the production of animal feed or the consumption of diesel fuel. The most environmentally efficient strategies are livestock reduction and conversion to organic farming. These strategies lead to a 25% decrease in the climate change indicator. However, this decrease is not enough to meet their national objectives and is still limited for the land use indicator.

3.3. Waste Management

Waste management is examined using the LCA method, which assesses the environmental effects of a product or process from its creation to its disposal. This methodology is utilized for municipal solid waste (MSW). Lundie & Peters (2005) analyzed the environmental impacts of various waste management options, including home composting, centralised composting, and codisposal of food waste, highlighting key environmental issues. They found that the lowest acidification (3.3×10^{-3} kg SO_2-eq./fu) and eutrophication (9.8×10^{-3} kg P-eq./fu) impact home composting compared to other waste management practices.

The applications of these are figuring out the best ways to handle trash in different areas (Miliūte & Staniškis, 2009; Omid et al., 2017; Grzesik, 2017; Avarand et al., 2023). Miliūte and Staniškis (2009) employed the lifecycle assessment (LCA) methodology to construct a model and examine various waste management scenarios to determine if regional conditions affect the waste management hierarchy. The scenario with the lowest environmental impact was recycling and incineration (RI-4). It had the lowest environmental impacts compared to other scenarios in four categories: global warming (4617 tonne CO_2-eq.), acidification (24 tonne SO_2-eq.), eutrophication (319 tonne O_2-eq.), and photo-oxidants (-11 tonne C_2H_4-eq.). Omid et al. (2017) employed the LCA methodology to evaluate the ecological consequences of waste management systems in a specific area. Four scenarios were identified, and Scenario 4 (consisting of source separation 14%, composting 30%, municipal recycling facility (MRF) 20%, energy recovery 10%, and landfilling 26%) was found to have the least impact. If government assistance is not accessible, it is advisable to opt for the third scenario, which involves source separation at a rate of 14%, composting at a rate of 30%, material recovery facility (MRF) at a rate of 20%, and landfilling at a rate of 36%.

Grzesik, in the year 2017 The modeling results indicate that both landfilling and incineration of residual waste have a detrimental effect on the environment. Nevertheless, incineration has a significantly smaller detrimental effect compared to landfilling. The major impact categories associated with landfilling are photochemical ozone formation (3.5×10^{14}PE), global warming ($6.42\text{x}10^{13}$PE), eutrophication (6.51×10^{13}PE), and human toxicity ($4.04\text{x}10^{13}$PE). On the other hand, significant impact categories for incineration include eutrophication (3.45×10^{5}PE), photochemical ozone formation (13.97×10^{5}PE), acidification (3.57×10^{5}PE), and human toxicity (3.45×10^{5} PE). In their study, Avarand et al. (2023) assessed the life cycle of waste management in Rasht city and determined the most effective strategy for developing its waste management system. The findings revealed that scenario 4, which involved 40% composting, 25% recycling, 20% sanitary landfill, and 15% waste incineration, had the greatest positive impact on the environment. The study revealed that scenario 4, which involves a decrease in landfills, has the most significant beneficial impact on the environment. This scenario results in both energy generation and material retrieval.

Ali et al. (2016) employed LCA to assess the transportation, treatment, and disposal of hospital solid waste. The methods evaluated included landfilling, incineration, composting, and material recycling. The evaluation of these methods was conducted with respect to their greenhouse gas emissions. Landfilling and incineration proved to be the least favorable options for final waste disposal, while composting and material recovery demonstrated significant reductions in emissions. The evaluation of different scenarios determined that an integrated system, which includes composting, incineration, and material recycling, is the most optimal solution. Wang et al. (2020) evaluated the past impact of municipal solid waste (MSW) management in Nottingham on global warming using LCA from April 2001 to March 2017. The LCA findings demonstrate a consistent decline in greenhouse gas (GHG) emissions from municipal solid waste (MSW) management over the course of the study. This reduction can be attributed to advancements in waste collection, treatment, material recycling, and waste prevention. The improvements led to a decrease in greenhouse gas (GHG) emissions from 1076.0 kg CO_2–eq./t of municipal solid waste (MSW) (or 498.2 kg CO_2–eq./Ca) in 2001/02 to 211.3 kg CO_2–eq./t of MSW (or 76.3

kg CO_2–eq./Ca) in 2016/17. An additional decrease of -142.3 kg CO_2-eq./t of MSW (or -40.2 kg CO_2-eq./Ca) could be attained by segregating food waste from incinerated waste, processing organic waste through anaerobic digestion, and pre-treating incinerated waste in a material recovery facility.

Corrado et al. (2017) highlighted the importance of enhancing the coherence of food loss accounting in LCA studies to ensure precise and dependable outcomes. Several approaches have been employed to analyze the environmental consequences of food waste, emphasizing the need for a consistent framework to improve accuracy and enable easier comparisons in LCA studies. To enhance the overall effectiveness, Corrado et al. (2017) recommended that LCA practitioners adopt a systematic approach when accounting for food loss, ensure accurate modeling of waste treatments, and prioritize transparency throughout the modeling process. Researchers can assess the strengths and weaknesses of different approaches to modeling food loss across the supply chain by measuring the environmental impact of food using LCA and evaluating food system management strategies. The main goal is to minimize primary production waste and reduce the overall environmental burden.

In their study, Garbounis et al. (2022) conducted a LCA to measure the environmental effects of seven different approaches for managing Wasted Plastic Pesticide Containers. The researchers then ranked these scenarios based on their environmental footprints. Collecting and recycling WPPC separately has been found to have the lowest net environmental impacts. Scenarios 5 and 6 emerged as the next environmentally optimal technologies, with a combination of recycling and either incineration or landfilling. However, it is worth noting that the landfilling scenario had the most significant environmental impacts.

Haupt et al. (2018) employed material flow analysis (MFA) as the foundation for the LCA, allowing for assessing emissions and impacts of recycling processes based on their inputs. The main objective is combining MFA and LCA to assess environmental efficiency of waste management systems. The framework thoroughly evaluates entire waste management systems by analyzing real waste flows. This analysis offers valuable information on the environmental effects of various recycling processes, which can assist policymakers in making informed decisions regarding waste management.

3.4. Manufacturing

The utilization of LCA in the manufacturing sector is varied and complex. Within the domain of sustainable manufacturing, LCA plays a crucial role in assessing the eco-efficiency and environmental consequences. This procedure offers valuable insights into the environmental efficiency of manufacturing processes, aiding in the identification of areas that can be enhanced and optimized. Bunnak et al. (2016) conducted a comparison between fed-batch (FB) and perfusion-based processes in the production of monoclonal antibodies (mAb). It was discovered that the FB process had a greater level of environmental friendliness compared to the perfusion-based process, even though it had a slightly higher cost of goods sold (COGS) due to a significantly reduced environmental impact. The perfusion process exhibited greater water consumption (35% higher), energy demands (17% greater), and CO_2 emissions (17% higher) in comparison to the fed-batch process, rendering it less environmentally sustainable than the FB process.

Schoeneberger (2024) conducted a study where they utilized a combination of LCA and techno-economic analysis (TEA) metrics to measure the greenhouse gas (GHG) emissions, water usage, and lifetime costs of different technologies across different scenarios. The study revealed that the industrial sector plays a substantial role in global carbon dioxide emissions, with fossil fuels accounting for 73% of its energy composition. The industrial sector in the United States is the primary source of greenhouse gas emissions among all economic end-use sectors. The decarbonization of the industrial sector presents difficulties as a result of varied manufacturing processes, expensive equipment, and competitive markets for products. Significantly, around 50% of manufacturing emissions in the United States can be attributed to the processes involved in generating heat. Industries can utilize Life Cycle Assessments (LCAs) to measure the amount of greenhouse gas emissions. Malmodin et al. (2010) reported that the combined CO_2 equivalent emissions from Information and Communication Technology (ICT) and its subsectors (Mobile telecom, Fixed telecom, PCs) in 2007 were 80 million metric tons, 120 million metric tons, and 250 million metric tons, respectively. Malmodin & Lundén (2018) discovered that the carbon footprint of the intensity metrics for the ICT sector was 134 kg CO_2eq./sub in 2007, 107 kg CO_2eq./sub in 2010, and 81 kg CO_2eq./sub in 2015.

The Entertainment and Media (E&M) sector, including TV, Printed Media, and Other E&M Hardware, has emitted a total of 390, 300, and 130 million metric tons of CO_2-eq. emissions, respectively. These results were correlated with the electricity consumption for each sector. Depletion of resources occurs during manufacturing, which affects the carbon footprint. Egilmez et al. (2017) discovered that the amount of carbon emissions steadily rose from 1970 to 2011. Unfortunately, the rapid increase in economic output obscured the potential advantages derived from reduced CO_2 intensities. The examination of industry data reveals that the five manufacturing sectors with the highest total carbon footprint share are "petroleum refineries," "Animal (except poultry) slaughtering, rendering, and processing," "Other basic organic chemical manufacturing," "Motor vehicle parts manufacturing," and "Iron and steel mills and ferroalloy manufacturing." In their study, Cheah et al. (2013) specifically examined the production of footwear and the resulting emissions. They determined that the carbon footprint of a standard pair of running shoes made from synthetic materials is estimated to be between 11.3 and 16.7 kg CO_2-eq. per pair. The predominant portion of this impact is generated during the materials processing and manufacturing stages, constituting approximately 29% and 68% of the overall impact, respectively. This information helps stakeholders develop strategies to reduce their impact on the environment.

LCA facilitates comparing various manufacturing processes, such as fed-batch and perfusion-based processes, to assess their life cycle costs and environmental impacts. The comparative analysis provides industries with the necessary information to make well-informed decisions about process selection, taking into account sustainability criteria; the results obtained in the study conducted by Amato et al. (2021) in the agricultural sector were not intended to discourage the development of alternatives for enhancing agricultural residues, but rather to highlight the importance of environmental sustainability aspects. The implemented LCA demonstrated the substantial impact of transitioning to renewable energy and the urgent need to identify ecological agents for the efficient and environmentally sustainable production of bio-based products. In addition, LCA can be combined with other tools, such as environmental support tools, to improve sustainability assessments and decision-making in the manufacturing sector.

3.5. Energy

The energy sector holds great significance, and it is essential to prioritize utilizing LCA in every aspect of its production, distribution, and consumption. The energy sector is interconnected with other sectors; 35% of the papers prioritize studying cumulative energy demand and its relationship to climate change (Lotteau et al., 2015). In 2010, Malmodin et al. found that the amount of electricity used by Information and Communication Technology (ICT) and its subsectors (Mobile telecom, Fixed telecom, PCs) in 2007 was 60 TWh, 160 TWh, and 260 TWh, respectively. The LCA is crucial for analyzing national energy systems' environmental impacts, including electricity, heat, and transportation. It comprehensively explains these impacts; to achieve the transition to a low-carbon economy in Germany by 2025, there needs to be a substantial decrease in greenhouse gas emissions by 85% compared to the levels recorded in 1990. Decarbonization strategies that exclusively target greenhouse gas (GHG) emissions may transfer the environmental burden to other forms of impact. This emphasizes the significance of taking into account a wider array of environmental impacts (Baumgärtner et al., 2021).

Furthermore, the geothermal sector has implemented LCA guidelines in order to enhance the consistency of outcomes across various renewable energy technologies (Parisi et al., 2020); they established standardized guidelines for conducting life cycle assessments (LCAs) of geothermal systems to ensure consistent outcomes across various renewable energy technologies. These guidelines provide technical advice on the methodological options, stages of the life cycle, and important components of LCA for geothermal energy production. Following these guidelines makes it possible to achieve comparability between LCA results obtained from different geothermal systems and other forms of renewable energy technologies. The SecMOD framework combines multi-sector energy system optimization with LCA, offering a comprehensive method for analyzing energy systems (Reinert et al., 2022). This integration enables a gradual expansion of systems by incorporating additional products and processes to analyze specific processes and interactions within a particular sector. The SecMOD framework considers the existing infrastructure, making it appropriate for optimizing newly developed and already established projects (Reinert et al., 2022).

Wang et al. (2024) conducted a comprehensive analysis of the environmental impact of the DES system on an actual project using GaBi software. The study highlights that the operation phase has the greatest environmental impact, accounting for 78.37% of the overall combined environmental impact, with the fuel production phase following closely behind. The energy production process has significant environmental consequences, such as resource depletion and climate change. To address these issues, the LCA framework can be utilized to identify areas of high impact and develop strategies to mitigate the environmental effects of energy production sector.

3.6. Packaging

LCA is an essential tool for the packaging industry. It allows for a thorough evaluation of materials and systems, as well as guidance for the development of sustainable packaging solutions. Multiple studies have demonstrated this, as shown in Table 3. LCA provides a thorough approach to evaluate the environmental impact of packaging, starting from the extraction of raw materials and ending with its disposal at the end of its life; by implementing all of the suggested enhancements into the packaging system, the environmental impact can be reduced by 18-45% compared to the current system (Bovea et al., 2005). The comprehensive analysis enables the packaging industry to assess the sustainability of different materials, such as bioplastics, glass, and metal, by evaluating their environmental impact at every stage; in their study, Cappiello et al. (2021) discovered that the bioplastic system outperforms both fossil-based systems and multilayer carton in several categories, including climate change, ozone depletion, human toxicity, freshwater eutrophication, particulate matter, and land use.

LCA, allows industries to make well-informed decisions that decrease environmental burdens by identifying environmentally friendly alternatives; Laso et al. (2017) identified that the most significant stages in the life cycle were the manufacturing of aluminium cans for packaging and the production of extra virgin olive oil, as well as the handling of packaging waste. And suggested implementing measures such as recycling packaging. Studies indicate that reducing the utilization of materials in packaging design is essential, as the extraction and production of these materials have a substantial impact on the environment; Molina-Besch & Pålsson (2015) discovered that companies frequently embrace green packaging for its economic advantages, yet face challenges in assessing trade-offs and environmental benefits due to both internal and external obstacles, LCA assists in identifying the most ecologically sustainable packaging choices by evaluating the complete life cycle of packaging. Despite the resource-intensive nature of LCA methodology, it directly contributes to reduce the packaging environmental impacts by offering valuable insights for sustainable design.

3.7. Transportation

The application of LCA has demonstrated its efficacy in assessing various transportation modes, including ships and tankers. According to Quang et al. (2021), the emissions and impacts resulting from shipbuilding, ship maintenance, and transportation activities are relatively smaller compared to the impacts caused by ship operation and material consumption. LCA offers policymakers essential data to mitigate greenhouse gas emissions and air pollution by examining vehicle emissions, energy consumption, and alternative transportation options. In their study, Samaras and Meisterling (2008) evaluated the GHG emissions throughout the life cycle of plug-in hybrid vehicles. They discovered that these vehicles achieve a 32% reduction in GHG emissions compared to conventional vehicles. However, the reduction in emissions is relatively small when compared to traditional hybrids. Batteries play a crucial role in plug-in hybrid vehicles, and the greenhouse gas emissions linked to the materials and production of lithium-ion batteries contribute to 2-5% of the total emissions throughout the life cycle of these vehicles. The longevity of electricity generation infrastructure means that choices made within the next ten years regarding electricity supplies in the power sector will have a significant impact on the potential for substantial reductions in greenhouse gas emissions through the use of plug-in hybrid vehicles for many decades to come (Samaras & Meisterling, 2008).

LCA is used in road transportation to evaluate noise pollution, demonstrating its adaptability in assessing the environmental impacts of various transportation choices. The health impacts of transportation noise are substantial. They should be considered in the LCA of road transportation and other environmental measures relevant to health outcomes. Ongel (2015) determined that the characterization factors for the nine municipalities in Istanbul varied from 0.005 to 0.09 healthy years lost per person. These factors were calculated based on the amount of noise emitted per meter of each highway segment for a duration of one year, measured in milliwatts (Ongel, 2015). The maritime industry utilizes LCA to assess the environmental impact of activities within the sector; Del Pero et al. (2023) discovered that although the production stage of Yacht superstructures has a greater impact, the innovative solution enables a substantial reduction in GHG throughout the entire life cycle (over 16%). This reduction is primarily due to a decrease in fuel consumption and lower CO_2 exhaust emissions during operation.

Furthermore, Folęga & Burchart-Korol (2017) have employed LCA to evaluate the environmental effects of road transportation; they examined the emissions of greenhouse gases from passenger cars on roads, finding that the emissions amount to 34.2 kilograms of carbon dioxide equivalent per functional unit. 80% of emissions are attributed to the production and consumption of petrol. The LCA method reveals that car fuel emissions are the primary cause of harm to human health and the ecosystem, with petrol production responsible for 66% of natural resource usage. Sopha et al. (2016) conducted a study on evaluating the impact of motorcycles by considering one passenger per kilometer (pkm) as the functional unit. They estimated the resource consumption and emissions throughout the entire life-cycle of a motorcycle. The study revealed that the operation (usage stage) of the motorcycle has had the greatest impact on global warming potential (GWP) and acidification potential (AP), whereas the manufacturing stage has had the greatest impact on human toxicity potential (HTP). Their paper also examines potential interventions pertaining to the manufacturing process, fuel, and usage of the motorcycle to mitigate its environmental impacts.

4. Discussion

Previous studies have shown that Life Cycle Assessment (LCA) is a highly effective tool for promoting sustainability in various industries, including construction, wastewater treatment, agriculture, waste management, and manufacturing. In addition, LCA can be enhanced by incorporating various aspects to promote long-term sustainability. There is no previous study that provides a comprehensive analyze environmental evaluation studies that have utilized life cycle assessment in different domains. This review offers a foundation for further development of life cycle assessment by integrating it with analytical and evaluative tools in various fields. This integration would help address existing gaps in the life cycle assessment methodology. The Life Cycle Assessment (LCA) method has various limitations that necessitate integrating with other assessment methodologies. Assessing impact categories in their current form often lacks consideration for socioeconomic factors. Therefore, it is necessary to utilize supplementary methodologies such as the Regional Sustainability Assessment Methodology (RSAM).

The construction sector utilizes the LCA approach to support the implementation of the circular economy. This approach extends beyond the construction industry and entails integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA). The research conducted by Inharwararak and Stravoravdis (2023) has demonstrated that the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) results in enhanced construction project management. This integration improves efficiency, reduces costs, promotes sustainability, and enables more precise environmental impact evaluations. These benefits are evident in both the economic and environmental domains.

Outdated inventory data often poses a challenge in conducting Life Cycle Assessment (LCA) studies in agriculture. To address this issue, dynamic modeling techniques are necessary to accurately capture the changing environmental impacts. In addition, it is important to note that life cycle assessment (LCA) may not comprehensively consider the interactions that occur within cropping systems. This can result in uncertainties and limitations when evaluating the environmental effects of agricultural practices (Goglio et al., 2017). In order to fill this void, scientists have devised comprehensive methods such as the Model for Integrative Life Cycle Assessment in Agriculture (MiLA) to consider the interplay between crops and the cycling of nutrients within agricultural systems. This improves the precision of sustainability evaluations in the field of agriculture.

Within the realm of waste management, Life Cycle Assessment (LCA) serves as a valuable instrument for assessing the ecological consequences of various waste management scenarios (Grzesik, 2017). Nevertheless, LCA alone may not encompass all pertinent variables, such as the risks posed by pathogens in wastewater management. Therefore, it is imperative to incorporate quantitative microbial risk assessment (QMRA) in order to thoroughly evaluate the environmental and health consequences of wastewater treatment processes (Harder et al., 2014). LCA neglects to comprehensively assess the various effects in areas such as wastewater systems, emphasizing the necessity for holistic strategies such as evaluating the economic and environmental viability of submerged anaerobic membrane bioreactors, which need more research and study.

The Packaging Impact Quick Evaluation Tool (PIQET) is an environmental assessment tool specifically designed for food packaging. Its purpose is to aid decision-making during the development of packaging by providing a comprehensive evaluation of its environmental impact (Molina-Besch & Pålsson, 2020). By combining PIQET with LCA, stakeholders in the food packaging industry can evaluate the ecological consequences of various packaging choices and make well-informed choices to reduce environmental footprints while preserving packaging functionality and efficiency. There is a need to make the assessment cover the economic aspects side by side with the environmental aspects of the packaging sector.

Integration of various methodologies with Life Cycle Assessment (LCA) is necessary in the manufacturing sector to overcome the inherent limitations of LCA and achieve a more thorough evaluation of sustainability aspects in manufacturing industries. Incorporating methodologies such as life cycle costing, multi-sector system optimization, sustainability principles, LCA-based frameworks, and SLCA with traditional LCA methodologies is crucial for addressing the significant shortcomings of LCA and achieving a more thorough assessment of sustainability aspects in the manufacturing sector. By integrating these approaches, scholars and professionals can carry out comprehensive sustainability evaluations, taking into account ecological, financial, and societal aspects to advance sustainable practices in the manufacturing sector.

Researchers have suggested combining life cycle assessment (LCA) with geographic information systems (GIS) in transportation to overcome spatial resolution difficulties encountered in LCA studies within the transportation industry (Molina-Besch & Pålsson, 2020). By integrating LCA with GIS, researchers can improve the accuracy and precision of LCA analyses, allowing for a more thorough evaluation of the environmental effects of transportation systems in various geographic areas. Moreover, it is imperative to incorporate noise pollution and social life cycle assessment (LCA) in future studies due to the direct correlation between the community and the local transportation sectors.

A comprehensive evaluation is particularly crucial in the energy sector because of its direct and indirect interconnections with all other sectors. The Life Cycle Assessment (LCA) studies in this field are crucial because they provide valuable information beyond just energy production and consumption. These studies consider geographic, social, economic, and efficiency aspects. A comprehensive and forward-looking methodology is created by combining LCA with the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operation Index (EEOI). This integration is crucial for analyzing shipping operations' environmental effects and energy efficiency. By utilizing the combined perspectives of Life Cycle Assessment (LCA), Energy Efficiency Design Index (EEDI), and Energy Efficiency Operational Indicator (EEOI), researchers can thoroughly evaluate the energy efficiency and environmental responsibility of maritime transportation. This combination not only emphasizes the importance of environmental factors in maximizing energy efficiency in shipping, but also confirms the essential role of Life Cycle Assessment (LCA) in improving energy strategies in the maritime industry.

The emphasis was on studies that demonstrated the practical application of Life Cycle Assessment (LCA) in combination with other models to evaluate environmental impacts and present the key findings of each study. This approach aims to identify opportunities for enhancing LCA methodologies and improving environmental impact assessments across various sectors and geographic regions. In recent decades, there has been an increasing interest in sustainability issues among government bodies and leaders in the private sector. The growing concern has highlighted the need for innovative approaches to tackle sustainability issues. Life Cycle Sustainability Assessment (LCSA) is an increasingly acknowledged and promising approach. Unlike conventional LCA, which focuses mainly on environmental impacts, Life Cycle Sustainability Assessment (LCSA) offers a more holistic perspective. The approach integrates environmental, social, and economic factors into the product design and evaluation process, aiming to achieve a more sustainable outcome (Muthu, 2021).

The environmental consequences of human activities are a critical concern that must be promptly and seriously addressed. In order to assess the magnitude of this influence, well-established methodologies such as LCA are employed, adhering to specific international standards such as ISO 14040:2006. Although it is possible to quantitatively evaluate the environmental impact, assessing the economic and social dimensions of sustainability is more difficult. Muthu pointed out in 2021 that the Life Cycle Sustainability Assessment (LCSA) methodology lacks universally accepted benchmarks. The absence of these benchmarks emphasizes the need for thorough research in multiple fields to establish comprehensive standards that encompass all aspects of sustainability. Through this approach, LCSA can efficiently direct researchers towards embracing sustainable practices and solutions, thereby making a valuable contribution to a sustainable future.

The economic viability of a project can be assessed by considering three key factors: the initial investment required, the ongoing expenses for operation and maintenance, and the costs associated with disposal. The overall financial sustainability and feasibility of any venture are significantly influenced by these factors (Martínez-Orgániz et al., 2024). Initial capital costs pertain to the project's establishment, whereas operating and maintenance costs encompass the ongoing expenses necessary for the project's smooth operation (Rajpurohit, 2024). Disposal costs refer to the financial burdens that arise at the end of a project's lifespan when removing or decommissioning its components (Chianese, 2024). Through a comprehensive examination of these three fundamental components, individuals with a vested interest can make well-informed choices regarding the sustained prosperity and financial feasibility of their undertakings.

The social dimension is the third aspect of LCSA. The evaluation of this dimension can be conducted using Social Life Cycle Assessment (S-LCA), which is a methodology that quantifies the social impacts of products or services across their entire life cycle, encompassing the stages of raw material extraction to disposal. The primary objective of S-LCA is to evaluate the impact on social aspects, including labor conditions, human rights, and community involvement. The Social Life Cycle Assessment (S-LCA) improves traditional Life Cycle Assessments (LCAs) by incorporating social factors, resulting in a more thorough understanding of the overall effects of products or services (Ashby, 2024; Cellura, 2024; Di Noia et al., 2024).

When conducting a Life Cycle Sustainability Assessment (LCSA), it is essential to take into account both the economic and social aspects in addition to the LCA. By systematically integrating these three dimensions in a comprehensive manner, researchers can elevate the benchmarks for environmental aspects as well as economic and social dimensions, thereby promoting a more all-encompassing approach to sustainability. Policymakers and stakeholders should strive to achieve this integration in order to enable organizations to make well-informed decisions for a sustainable future.

5. Conclusion

This review examines the widespread use of LCA in assessing environmental effects in different industries by analyzing 51 scientific papers. LCA is invaluable for advancing sustainability in diverse sectors such as construction, wastewater treatment, agriculture, waste management, and manufacturing. Nevertheless, it is important to note that this approach has certain limitations, including its failure to consider socioeconomic and geographic factors. To tackle these issues, additional approaches such as the Regional Sustainability Assessment Methodology (RSAM) are required. Integrating LCA with Building Information Modeling (BIM) can enhance project management in the construction sector, leading to improved efficiency and cost reduction. In agriculture, dynamic modeling techniques and quantitative microbial risk assessment are essential to capture the evolving environmental effects accurately. The Packaging Impact Quick Evaluation Tool (PIQET) assists in decision-making during the development of food packaging. Meanwhile, integrating LCA with Geographic Information Systems (GIS) in transportation can enhance accuracy and precision.

LCA studies play a vital role in the energy sector by offering valuable insights beyond energy production and consumption. By integrating Life Cycle Assessment (LCA) with the Energy Efficiency Design Index (EEDI) and Energy Efficiency Operation Index (EEOI), researchers can assess the environmental impact and energy efficiency of shipping operations. The LCSA approach incorporates a comprehensive viewpoint that considers environmental, social, and economic considerations when designing and evaluating products. It focuses on the ecological impacts of human actions and does not have widely agreed-upon standards. A project's economic feasibility is evaluated by considering the initial capital investment, recurring expenses, and costs associated with disposal. Social Life Cycle Assessment (S-LCA) measures the social effects of products or services throughout their entire life cycle. Incorporating these dimensions facilitates a more holistic approach to sustainability.

The study emphasizes enhancing LCA methodologies to overcome limitations and integrate additional factors. Subsequent investigations should prioritize enhancing the accuracy and inclusiveness of LCA, formulating novel integration methodologies, and broadening its implementation across additional industries. Through the ongoing improvement of LCA practices, we can enhance our ability to promote sustainable development and responsible management of resources globally.

Future research should prioritize enhancing the socioeconomic and geographic integration of Land Use and Construction Assessment (LCA) methodologies, refining dynamic modeling techniques in agriculture, expanding the integration of Building Information Modeling (BIM) and LCA in construction, developing comprehensive decision-support tools, standardizing Life Cycle Sustainability Assessment (LCSA) practices, assessing long-term sustainability outcomes, exploring new industry applications, and improving public policy and corporate strategies. The purpose of these suggestions is to enhance the accuracy and usability of LCA findings, establish universally accepted standards, evaluate long-term sustainability results, investigate new industry uses, and improve public policy and corporate strategies to develop more efficient sustainability initiatives and regulatory frameworks.

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