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Life Cycle Assessment and Sustainable Construction: A Comprehensive Review from Theoretical Foundations to Practical Strategies and Innovative Methods

Yaşam Döngüsü Analizi ve Sürdürülebilir İnşaat: Teorik Temellerden Uygulamalı Stratejilere ve Yenilikçi Yöntemlere Kapsamlı Bir İnceleme

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ABSTRACT

The building sector significantly affects the environment through its reliance on natural resources and its role in driving greenhouse gas emissions. Buildings are responsible for a large portion of global energy consumption, and their construction and operation contribute heavily to environmental degradation. Implementing environmentally friendly building practices is critical to mitigate these adverse impacts and ensure sustainable development. Life Cycle Assessment (LCA) is an approach to assess the environmental impacts of goods and services throughout their lifespan, from raw material extraction to disposal. This procedure includes resource use, energy consumption, waste generation, and carbon emissions. LCA's evaluation of a building's environmental impact includes energy usage and carbon emissions from material manufacturing, transportation, construction, operation, and end-of-life disposal. This literature review consolidates and synthesizes the current knowledge about LCA in the building sector. It addresses various methodological approaches to conducting LCA, categories of environmental impacts considered, and insights and limitations of previous studies. The aim of this review is to provide a better understanding of the position of life cycle analysis in the construction industry. It offers guidance for promoting sustainable building practices and informs future research, environmentally friendly design, construction, and policy-making. These considerations will guide future approaches towards a more sustainable environment.

Keywords: Construction practices, environmental impact, life cycle assessment (LCA), methodological approaches, sustainability.

ÖZ

İnşaat sektörü, doğal kaynaklara olan bağımlılığı ve sera gazı emisyonlarına katkısı nedeniyle çevre üzerinde önemli bir etkiye sahiptir. Binalar, küresel enerji tüketiminin büyük bir kısmından sorumludur ve inşaatı ve işletilmesi çevresel bozulmaya büyük ölçüde katkıda bulunmaktadır. Çevre dostu inşaat uygulamalarının hayata geçirilmesi, bu olumsuz etkilerin azaltılması ve sürdürülebilir kalkınmanın sağlanması açısından kritik öneme sahiptir. Yaşam Döngüsü Değerlendirmesi (LCA), malların ve hizmetlerin yaşamları boyunca çevresel etkilerini değerlendiren bir yaklaşımdır; bu süreç, ham madde çıkarımından atık bertarafına kadar tüm aşamaları kapsar. Bu prosedür, kaynak kullanımı, enerji tüketimi, atık üretimi ve karbon emisyonlarını içerir. LCA'nın bir binanın çevresel etkilerini değerlendirmesi, malzeme üretimi, taşınması, inşaatı, işletilmesi ve son atık yönetimi gibi aşamalarda enerji kullanımı ve karbon emisyonlarını içerir. Bu literatür taraması, inşaat sektöründe LCA hakkında mevcut bilgileri derleyip sentezlemektedir. LCA yapma yöntemleri, dikkate alınan çevresel etki kategorileri ve önceki çalışmaların sunduğu içgörüler ile sınırlamaları ele alınmaktadır. Bu incelemenin amacı, inşaat endüstrisindeki yaşam döngüsü analizinin yerini daha iyi anlamaktır. Ayrıca, sürdürülebilir inşaat uygulamalarını teşvik etmek için rehberlik sunar ve gelecekteki araştırmalar, çevre dostu tasarım, inşaat ve politika yapımına yönelik bilgilendirme sağlar. Bu hususlar, daha sürdürülebilir bir çevreye yönelik gelecekteki yaklaşımlara rehberlik ederek, daha verimli ve etkili uygulamaların uygulanmasına olanak tanıyacaktır. Bu süreç, aynı zamanda çevre bilincinin arttırılması ve sürdürülebilir yapıların yaygınlaştırılması için önemli fırsatlar sunmaktadır.

Anahtar Kelimeler: İnşaat uygulamaları, çevresel etki, yaşam döngüsü değerlendirmesi, metodolojik yaklaşımlar, sürdürülebilirlik.

Introduction

Today, the world's population is increasing; simultaneously urban development processes are hastening, and natural resource production challenges its limits.The current paradigm reveals that, as a primary resource user, the construction industry has attracted significant interest among researchers because of challenges like resource scarcity and climate change. In light of this urgent matter, many international organizations and governments are significantly increasing their efforts to help reduce the damage to the natural environment in this area. For many years, there has been much effort to perfect the scientific and technological methods of measuring, mitigating, and eliminating building construction's environmental impacts. These techniques employ well-planned strategies to conserve the environment. Strategies in the environment to lessen factors of production effects consist of using materials that can be recyclable and renewable, lowering energy consumption, and minimizing waste. Sustainable construction is now recognized as important because it has benefits not only to the environment but also to the economy over the long run. Many sustainability efforts today are moving toward a core concept called life cycle assessment (LCA). LCA is a defined, broad, and systematic approach that, according to the United States Environmental Protection Agency (n.d.), is a methodology for assessing the environmental impacts of a product, service, or process throughout its entire life cycle. LCA involves the evaluation of a product or process in a more comprehensive way, covering the entire life cycle, from the extraction of raw materials, manufacturing, distribution, use, and final disposal or recycling. Thus, LCA is a kind of decision-making framework where full information about environmental impacts over the entire life-cycle of a range of products or processes is available. Different authors in the literature on LCA refer to this process in a variety of ways, for example, as the 'cradle-to-grave' approach (Ciambrone, 1997; Joshi, 1999). This figure illustrates the direct influence of LCA in assessing environmental impacts across all stages of a particular product or service life cycle. It covers all steps from the extraction of raw materials (called "cradle") to the end-of-life disposal or recycling ("grave"). LCA offers broad, reliable ecological footprint evaluations across the life cycle stage of a product. It enables the identification of possible improvements, hence promoting choices aligned with more sustainable approaches. During the system evaluation stage of every project, it is necessary to quantitatively model all components of the project, including resource and energy consumption, soil, air, and water emissions, and waste (ISO 14040:2006). Life cycle assessment provides a systematic approach that can control and mitigate the environmental damage of a product and process effectively by examining the product or process from the environmental perspective, with scientific reviews and substantial benefits to the economy and environmental protection. More accurate information is beneficial for the improvement of the product life cycle and process strategy development (Heijungs & Suh, 2002; WRI, 2008). Life cycle analysis as a technique is an applied and standardized methodological process that allows environmental stress assessment on a system scale (Finnveden et al., 2009). Environmental footprint assessments are widely embraced within the construction sector. This quality makes LCA an essential tool for architectural designers and constructors, as well as for policymakers looking for an analytical protocol with which to identify, assess, and interpret the innate environmental stress of any building paradigm. In addition, the greenhouse gas emissions, amount of water consumption, energy utilization rates, wastes generated in volume, and natural resource depletion scenarios provide places for finding potential areas that will minimize environmentally damaging impacts from their structure builders and architectural professionals. This can be achieved by utilizing renewable power sources or implementing designs that are more focused on efficient usage of resources; other methods include reusing materials previously discarded after being used once before. Moreover, the life-cycle analysis concept fosters a complete ecological impact overview for every chosen building during the whole actual life of the building, not only its structure related to the embodied energy and the carbon footprint during the material production but also includes the transportation stage. In the process of making decisions about the type of building or the building system, a thorough evaluation of the materials, design strategies, and different frameworks of the building materials should be considered in order to make the best choice according to environmental considerations. Hence, LCA is essential to the construction industry's efforts to promote environmentally friendly building practices and lessen the adverse effects of structures. Through a deep analysis process of the building's greenhouse gas effect investigation, LCA can be used to guide the choice of building design, choice of materials, and construction practices, thereby achieving the creation of ecological practices that are more friendly to the environment. This study of literature is the result of the investigation work of numerous other researchers and is a comprehensive and up-to-date review of LCA implementation in the building industry. The main aim of this study is to identify and unite the available knowledge on the use of LCA in the construction industry, which includes the different techniques, the environmental factors that are considered, and the fundamental results and obstacles brought out by earlier research. This report aims to guide decision-makers, researchers, industry experts, and policymakers in achieving sustainability goals in the building sector. By undertaking this review, the study seeks to improve comprehension of the significance of LCA in the construction sector and provide beneficial insights for forthcoming research and practical applications in sustainable building structure and construction.

Material and Methods

As part of this research, an extensive literature review was carried out using EBSCOhost, Google Scholar, Web of Science, and Scopus as educational databases. The search queries used in this review were "life cycle assessment," "energy," "construction," "environmental impact assessment," and "building materials." This review was limited to scientific articles published from 2000 to 2022 (Figure 1).

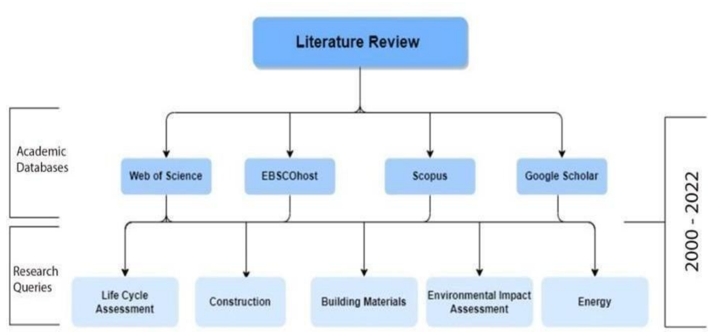

Figure 1. Overview of the research process as prepared by the authors

In this particular investigation, the literature evaluation was guided by the recommendations provided by PRISMA, which stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Figure 2). Based on these guidelines, this investigation conducted a broad literature review on employing LCA in the building sector. A comprehensive analysis was undertaken utilizing records sourced from three scholarly resources. The dataset consisted of 2656 records obtained from the Web of Science, 2928 recordings obtained from Scopus, and 2894 records obtained from Science Direct, resulting in a combined total of 8478 records. Before the initiation of the screening procedure, 508 duplicate records were systematically carried out. Additionally, 4608 records were carried out in the initial screening procedure based on the titles and abstracts. This left 3362 records eligible for full-text retrieval. Regrettably, 3274 reports could not be fully recovered. Subsequently, 88 articles underwent a detailed assessment of eligibility, resulting in the removal of 20 irrelevant reports. Ultimately, the systematic review included 68 studies relevant to the inquiry.

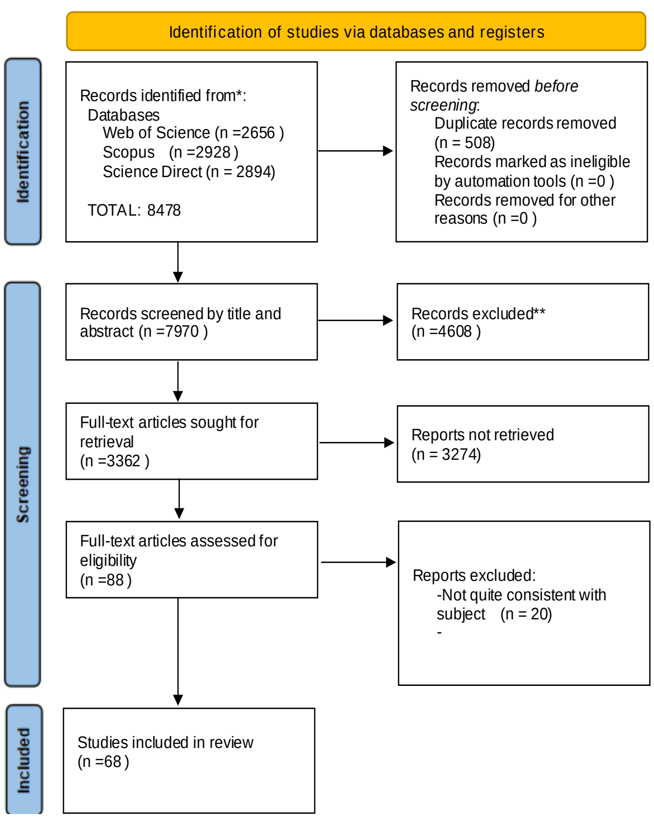

Figure 2. PRISMA

This research organizes LCA categories into the sections of Literature Review and Bibliometric Analysis based on certain grouping criteria. This categorization seeks to cohesively represent the extensive subjects in the literature and the keywords in the bibliometric analysis. Under the heading "In terms of Environmental Impact Assessment," environmental impact assessment encompasses methods and applications for analyzing environmental impacts. In the literature review, studies detailing environmental impacts have been summarized, while the bibliometric analysis visually represents the strong connections and relationships between environmental impacts. The keyword "environmental impact," which shows strong connections in the bibliometric analysis, is associated with the studies presented under this heading. Under the title "In terms of Energy Efficiency," energy analysis is related to studies that evaluate energy use and efficiency. Energy-saving strategies, performance analysis, and literature on energy efficiency are examined under this title. In the bibliometric analysis, the relationship and density between keywords related to energy efficiency are shown graphically. The keyword "energy efficiency" is associated with the studies discussed under this title. The heading "In terms of Building Material Assessment" encompasses the assessment of building materials, their environmental consequences, and performance studies. The literature study discusses the assessment of building materials for sustainability and different analytical approaches. The bibliometric study illustrates the relationships and impacts of keywords associated with construction materials. The term "building materials" pertains to the research conducted under this designation. The title "In Terms of Integrated Approaches to Life Cycle Assessment: Emphasis on Sustainability, Circular Economy, and Building Information Modeling (BIM)" presents a coherent view of sustainability, circular economy, and building information modeling (BIM) through integrated approaches. The literature review comprehensively examines these three concepts and integrated working approaches. In the bibliometric analysis, interactions and connections with key topics such as "sustainability," "circular economy," and "BIM" are graphically visualized. Three keywords are presented under this title as integrated approaches. The study structure identifies keywords with strong connections to the titles "Environmental Impact," "Energy Efficiency," and "Building Materials," while "Sustainability," "Building Information Modeling," and "Circular Economy" are other prominent topics in the literature that are comprehensively covered under the title of integrated approaches. This arrangement aims to ensure consistency between titles and groupings and to present the data comprehensively.

Bibliometric Analysis

Three databases—Web of Science, Scopus, and Science Direct—were utilized to examine the literature thoroughly. The review was supplemented with bibliometric analysis, performed using an open tool called VOSviewer. This study uses VOSviewer to construct graphical illustrations of the associations among various concepts in the literature review. This approach facilitates the identification of research gaps, visualization of the current knowledge state, and formulation of new research inquiries. Keyword analysis formed the co-occurrence of keywords regarding the research goal in 'RIS' format from the mentioned sources.

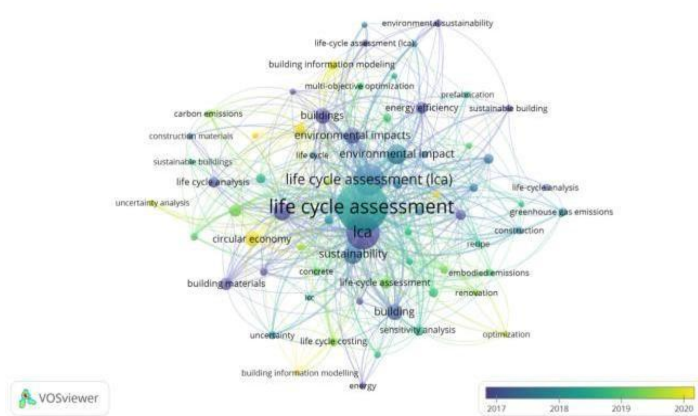

Figure 3. Co-occurrence network of keywords generated using VOSviewer, showing the relationships and clusters of terms relevant to the research goal

The co-occurrence of keywords catches the powerful link strength of keywords "environmental impacts," "energy efficiency," and "building materials." Besides these, other notable keywords are "sustainability," "circular economy," and" building information modeling (BIM)." (Figure 3). Figure 3 shows the intensity between the keywords. In the VOSviewer application, a comparison was made between co-authorship relationships and country affiliations. The VOSviewer analysis highlights the prominence of several countries, including China, Spain, Italy, and England (Figure 4). As depicted in Figure 4, the size of the bubbles corresponds to the strength of the connections among the studies from each country.

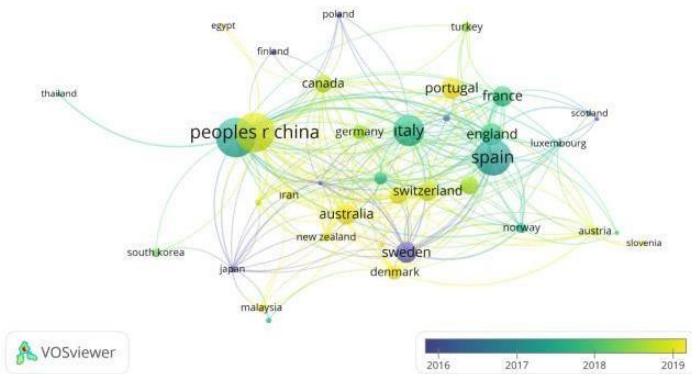

Figure 4. Co-authorship relationships and country affiliations visualized using VOSviewer

The study information in "txt" format was retrieved from the WOS database and utilized to generate a co-cited studies diagram shown as figure 5 using VOSviewer.

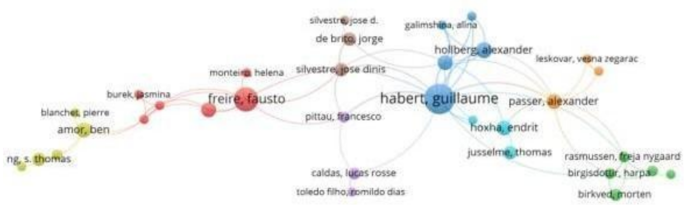

Figure 5. Co-cited studies network visualized using VOSviewer

Literature Review

The 1970s primarily focused on assessing and contrasting various consumer products; however, these studies made minimal contributions to the utilization phase (Guinée et al., 2011). During the early 1980s, the construction sector began adopting life-cycle thinking, prioritizing utilizing renewable resources (Bekker, 1982). In the 1990s, the Society for Environmental Toxicology and Chemistry (SETAC) spearheaded efforts to unite LCA practitioners and establish standards for the field's framework, method, and terminology. This ultimately improved the SETAC "Code of Practice." (Heijungs et al., 1992). During this time, SETAC's program significantly contributed to LCA's methodological and scientific advancement, strengthening its reputation as a responsible method for environmental impact estimations. The International Organization for Standardization (ISO)'s involvement in 1994 created the ISO 14040 series, published in 1997, to provide guidelines and general principles for conducting an LCA. Several years later, the ISO 14044, published in 2006, contains requirements and guidelines for carrying out LCA studies. In 2013, ISO 14025 was published, which provided guidelines for developing Type III environmental declarations, a type of LCA-based product environmental labeling. Since the beginning of the twenty-first century, LCA has been increasingly emphasized.

In the last decade, in addition to the standards ISO 14040, specific developments have been aimed at the construction industry (Kögler & Goodchild, 2004).In addition, many academic papers have significantly supported the development of LCA. Ciambrone (1997), for example, introduced the LCA methodology, data collection, interpretation, and impact assessment. According to Joshi (1999), the report included practical tips on how to do a life cycle assessment study, like the quality and uncertainty of data analysis. On the other hand, Curran (2018) offered his most recent version of a thorough manual on LCA studies, the review of existing standards and tools, and applications. Life Cycle Assessment is a widely used method to determine the environmental impact of products and systems. It has advanced through many influential academic and commercial contributions that enable LCA to be recognized as an essential tool for sustainable development due to the holistic appraisal of any kind of product or service.

Studies from LCA are classified according to studies that cover building sustainability. These sections of the building life cycle assessment help to provide valuable information about the various concepts and publishing goals on life cycle assessment in the construction sector. There exist classification systems, including the division of LCA studies based on the type of environmental impact assessment, energy analysis, and building material assessment. Environmental impact assessment is focused on the environmental impacts of a product or service, while energy analysis is assessing an entire system that uses all inputs and outputs as directly consumed. Several studies in the literature explore the integration of LCA and other approaches to support sustainable building practices caused by multiple construction materials and techniques. In addition, various studies in the literature explore the integration of LCA and other integrated approaches to support sustainable building practices.

In terms of Environmental Impact Assessment

Many studies have been carried out on the environmental impacts of building designs and construction projects in the context of environmental impact assessment. Citherlet et al. (2001) stated that an integrated study of building performance is required throughout the design phase to avoid creating buildings with unacceptable performance characteristics. Computer-aided simulation is the most efficient way to achieve this goal. This study provides a viable technique for assessing building performance, encompassing elements like comfort (including lighting, ventilation, and heating), room acoustics, and environmental impacts that can be implemented in the ESP-r design. In their comprehensive environmental LCA, Junnila & Horvath (2003) strove to establish the causal relationship between the potential environmental impacts of the various environmental life cycle components. This research assesses the main environmental impacts of a brand-new and upscale office building over 50 years. As the results show, electricity consumption and building material production have considerable environmental impacts, while construction and demolition have relatively small effects. Junnila (2004) aimed to determine and contrast the probable environmental impacts of an office building throughout its existence. The study's findings confirmed that a typical contemporary office building has many of the same environmentally critical life cycle phases and components, regardless of the design groups, contractors, or occupants. The emphasis by Wang et al. (2005) highlights the necessity of prioritizing environmental performance in the design procedure to mitigate the environmental impacts of buildings. The multi- criteria optimization method presented in this study could help designers create green buildings. The LCA methodology is utilized to evaluate design options on both ecological and economic bases. Using data from the German "Centre for Construction Costs," Matasci (2006) performed an extensive LCA on several buildings. This analysis mainly aimed to assign significant phases or components of the construction process that needed a high-level assessment and effort from an environmental point of view. LCA model designed by Gu et al. (2007) for building cooling and heating source systems. In addition to evaluating energy consumption, this model incorporates resource use and pollutant emissions, delivering a complete index for assessing the total environmental impact throughout the structure's lifespan. Moreover, Pons & Wadel (2011) categorized the construction of a wide variety of schools by analyzing their construction processes. They technically and sustainably analyzed the building technologies in a way that identified how they improved quality while reducing the environmental burden of buildings. As a result of their research, Cetiner & Ceylan (2013) proposed a new method to calculate the environmental impacts of residential building refurbishment in Turkey. The current study estimated the various environmental impacts of renovation techniques, and it helps people to approach the sustainable building topic within the Turkish housing typology. Moreover, several architectural parameters, such as window-to-wall ratio (WWR), building age, and face orientation, are analyzed. Finally, it is understood from the results that WWR is the most dominant factor that affects the percentages of the environmental performance achieved due to renovation. Furthermore, Jang et al. (2015) proposed a hybrid LCA example to perform a more exhaustive study of the embodied environmental impacts of constructions. Pushkar's (2015) aim was to look at the differences in the environmental impacts that a single module of a building is experiencing through a series of stages, which are supposed to be seen as the layers of a life cycle shearing. The research showed how individual steps in a building's cycle impact the environment and, therefore, gave more insights into the overall building design and construction methods being sustainable. Ali et al. (2015) carried out the Life Cycle Assessment, an analytical technique, to measure and evaluate the environmental impacts of common residential construction works in Egypt. Using life cycle assessment, Hong et al. (2016) studied the environmental impacts of 23 primary schools in South Korea. A parametric LCA technique has been suggested, according to Hollberg & Ruth (2016), that will allow architects to effectively design buildings where the environmental impacts are reduced. Also, Tummunia et al. (2018) conducted a comprehensive life cycle analysis of the environmental impacts of modular prefabricated houses in Italy. They have contributed a favorable opinion on sustainability in Italy through this study by giving an in-depth analysis of the positive and negative influence of such building practices on the environment. Lastly, Pamu et al. (2022) estimated the environmental implications of a residential structure in a significant Indian metropolis throughout the construction period.

In terms of Energy Efficiency

Several studies have been conducted to evaluate various energy efficiencies and consumptions in the design and construction of buildings from an energy analysis point of view. Fay et al. (2000) utilized lifecycle energy assessment to investigate the energy efficiency of various design concepts for a residential dwelling in Australia. Horita (2005) conducted an energy analysis on a bioclimatic dwelling for low-income families to determine potential areas for advancement in future large-scale residential initiatives in developing nations. Casals (2006) examined the fundamental requirements for regulatory and certification programs for buildings to regulate and limit energy consumption in the construction sector beneficially. Chen (2006) proposed a systematic approach to evaluating the life cycle energy efficiency of smart buildings. This approach solves a multi-criteria decision-making problem and provides useful information in assessing these buildings. Holtzhausen (2007) presents results of energy value comparison between different materials in order to determine what conclusions can be drawn by urbanists and architects for a longer-lasting building with a greater advantage towards the environment. Pearlmutter et al. (2007) have studied the potential for energy savings that could be attained by adopting bioclimatic building design in desert regions. The aim of the study was to evaluate bioclimatic strategies for sustainability practices in building construction while restraining energy consumption under local environmental criteria investigated. Furthermore, Mari (2007) investigated five distinct residential structures to determine the amount of embodied energy linked with the principal materials used in each construction project. Lee et al. (2009) laid the groundwork for a construction LCA program concentrating on energy usage and carbon dioxide emissions. The phrase net energy is introduced and employed in the study by Hernandez & Kenny (2010) for the built environment. This uses a technique that considers both the building elements' embodied energy and energy consumption during operation. The study suggested incorporating the net energy ratio (NER) into building design as a metric that considers the entire lifespan of the structure. The primary objective of the research conducted by Rossello-Batle et al. (2010) is to determine which operation phase most influences the life cycle of a tourism facility. An analysis was conducted on a subset of hotels' energy consumption, refuse generation, and carbon dioxide emissions over fifty years. Based on the findings, it was determined that the operational phase, which considers between 70 and 80 percent of the overall energy usage, had the most significant influence. When it comes to the process of how a building can be energy efficient, Dakwale (2011) argues that enhanced environmental performance allows all aspects that are responsible for increasing the efficiency of energy in a building to be incorporated through effective strategies. Even so, this work shows how to combine different data aspects like legal and voluntary regulations, rating systems for recognizing energy efficiency, and life cycle evaluations and simulations as part of the assembly/disassembly phase processes and materials selection. In an investigation executed in Lisbon, Bastos et al. (2014) did a study in Lisbon about energy efficiency and greenhouse gases from three typical urban buildings. They focused on homes and wanted to check the overall energy use during the buildings' life cycle. Their analysis helps them define what an "eco-friendly" building is—a home that produces minimal emissions throughout its life. Ge et al. (2015) conducted research in order to find the environmental impacts of building two museums in China with one of the lowest energy-saving. Among other things, the life LCA was done to find out the energy usage and greenhouse gas emissions connected to the museums. Rodrigues et al. (2018) performed a thorough LCA to measure the energy and carbon emissions an industrial building produces throughout its development. The LCA, presented by Tulevech et al. (2018), is related to a low-energy industrial building in Thailand seeking green building certification from the German Sustainable Building Council (DGNB). Also, Tummunia et al. (2018), in their investigation, performed an in-depth LCA for the energy efficiency of an Italian prefabricated home module and showed the energy efficiency of prefabricated housing as a key part of a sustainable energy system. Zhang et al. created the China Building Development Model, in which the authors analyzed the amount of carbon pollution and energy consumption due to the development of buildings in China. The researchers utilized the CBCM to investigate the trends in environmental impacts resulting from Chinese building construction between 2000 and 2016. Chang et al. (2019) accomplished the first comprehensive evaluation of a campus in the Asia Pacific region at Nanyang Technological University (NTU). Twenty-two academic buildings were subjected to a life cycle energy assessment. Emmanuel et al. (2020) investigated sustainable design principles and assessed the energy efficiency of a residential unit structure employing a life cycle energy analysis. Skillington et al. (2022) thoroughly reviewed measures related to embodied energy and greenhouse gas emissions in construction processes between the United Kingdom, Canada, Australia, and the United States. Their analysis aimed at recognizing differences among these regions from the perspective of methodologies and their longer-lasting implications for future industry developments.

In terms of Building Material Assessment

As for building material assessment, much research has been done in the field to find out the eco-profiles, characteristics and impacts of different construction materials. Nicoletti et al. (2022) conducted an LCA to compare ceramic tiling against marble tiles as a floor covering material to identify one with more environmentally preferable characteristics than another. Compared to marble tiles, ceramic tiles have a life cycle score of almost twice as low. In Holtzhausen's (2007) study, building materials with extensive use, including cement, steel, and aluminum, are examined for their embodied energy and determined in the parts of the building that use the most energy over its whole life. A study conducted by Mari (2007) examined the embodied energy of five residential structures that used concrete, brick, glass, and steel. According to the result, the building sector would significantly decrease its environmental impacts and embodied energy by using recyclable and reusable materials. Ardente (2008) offered a life cycle assessment of an insulating board made from kenaf fiber using international standards. In the conducted study, several types of insulation were compared. Using simulations, In their study, John et al. (2009) analyzed the impact of construction materials on the energy usage and global warming potential of four comparable office building designs throughout their life cycle: timber, steel, concrete, and timber plus. Bribián (2012) provided the findings of an LCA that compares the widely used construction materials to eco-materials across various impact categorizations. The objective is to improve awareness of building materials' energy and environmental needs, analyze their development potential, and advise on material selection for eco-designing new and renovated structures. In their analysis, Skullestad et al. (2016) evaluated the climatic impacts of reinforced concrete structures versus timber structures across four buildings, seeking to estimate the effect of each construction material on environmental sustainability. The analysis utilized LCA to gather relevant data. Furthermore, Estokovo et al. (2017) evaluated the environmental impacts of twenty masonry residential buildings concerning their installation materials. It has been determined that foundation materials are responsible for the most adverse environmental impacts. Li & Zheng (2019) examined, with the LCA approach, the carbon footprint of precast concrete pile products during their whole life cycle. Luo & Chen (2020) used an LCA-based carbon emission model to calculate the greenhouse gas emissions of residential construction materials in multiple regions.

In Terms of Integrated Approaches to LCA: Emphasis on Sustainability, Circular Economy and Building Information Modelling (BIM)

Several integrated studies and research attempts combined several methodologies to demonstrate comprehensive evaluations and perceptions in regard to sustainable construction activities. Li's (2006) study focused on the environmental impact of the consumption of natural resources and disruption in pollutant emissions between areas during the construction sector, aiming at finding new ideas to promote sustainable development. The analysis offers a unique LCA method, "region-type life cycle impact assessment (R-LCIA)," to comprehensively examine building environmental impacts. This can provide both the regional and overall environmental burden at different scales. In another study, Gu et al. (2008) developed the Life Cycle Green Cost Assessment (LCGCA) due to a demand for comprehensive evaluation systems that highlight sustainability in construction activities. An innovative method that combines LCA with a study of life cycle costs (LCC) makes it possible to assess the environmental and economic aspects of the buildings throughout their whole lives. This integrated approach redefines the frontiers of traditional LCA by combining concepts of LCC within a framework that allows the assessment of holistic sustainability performances. Furthermore, Wang et al. (2011) carried out a full LCA study in order to investigate the potential for combining Building Information Modeling (BIM) to accomplish a detailed life-cycle assessment of whole buildings. BIM tools and Ecotect can aid LCA by providing important base data and calculation means for an LCA. The life cycle carbon emissions model, abbreviated as the LCCE model, was conceptualized by You et al. (2011). The newly suggested model facilitates the estimation of the collective carbon footprint generated by all buildings within a city throughout the entire duration of their operational life. Review studies by Kuaa & Wong (2012) of a commercial building in Singapore revealed life-cycle assessment data with waste generation over the operating time frame. The research has also seen the compatibility between techniques of minimization, sorting, collection, and recycling for the building level. This analysis was informally reviewed against a policy framework of full solution provision. A conceptual structure was introduced by Collinge et al. (2013) to integrate the interior environmental quality (IEQ) impacts of an entire building into a life cycle analysis. The findings demonstrated that incorporating IEQ factors in the entire building LCA revealed internal effects in several life cycle impact assessment (LCIA) classifications equivalent to external effects. To ensure that all Canadian schools' exterior and structural systems undergo extensive sustainability evaluations, a paradigm combining the LCA and the Leadership in Energy and Environmental Design (LEED) program was proposed by Alshamrani et al. (2014). This model incorporates LCA into LEED and provides suitable LEED ratings. This helps the individual to make informed decisions and aids in creating building design and construction that is environmentally appropriate. Incorporating the LCA within BIM, Najjar et al. (2017) give a decision-making methodology within the context of the building that is very useful in sustainable development and environmental protection. An integrative LCA concept was proposed by Lee et al. (2017). This model integrates all life cycle assessment data related to building materials, structural components, and the complete building into a unified framework. Ghoroghi et al. (2022) proposed that integrating machine learning (ML) and LCA can significantly decrease environmental impacts. Lu et al. (2020) suggest that integrating BIM with LCA and LCC analysis offers a feasible technique for evaluating and optimizing buildings' economic and environmental impacts.

Other Methodological Approach

Other than discussing the different methods listed, supporting models and frameworks have been presented to ensure the life cycle assessment of buildings and indicate sustainable construction measures. A hybrid method for building life cycle evaluation was proposed by Treloar et al. (2004) that utilizes national input-output data to complement the gaps in standard LCA data. The primary objective of Kashkooli & Altan's (2010) paper is to provide a novel semi-quantitative technique for calculating the embodied and carbon building's environmental impacts and compare several LCA tools for the building industry. Wallhagen et al. (2011) demonstrate the implications of applying an LCA methodology to buildings during the initial stages of the design process. In another research, Means & Guggemos (2015) described a method for incorporating LCA data into early-stage design decisions for commercial structures, making a comparison to the existing LCA tools and databases, and outlining the "next stages" in creating an extensive LCA standard. Hu (2018) proposed a dynamic LCA framework that considers the temporal perspective and value preference of users. The methodology was then illustrated in an elementary school case study, showing the importance and insights of dynamic LCA as compared with conventional static LCA. Using life-cycle analyses, Pushkar et al. (2022) sought to choose an earthquake-resistant design that is ecologically friendly.

Results

After a comprehensive review of the existing literature, it became evident that a substantial amount of research has been dedicated to LCA in the building sector, indicating a notable emphasis on promoting sustainable building methods.

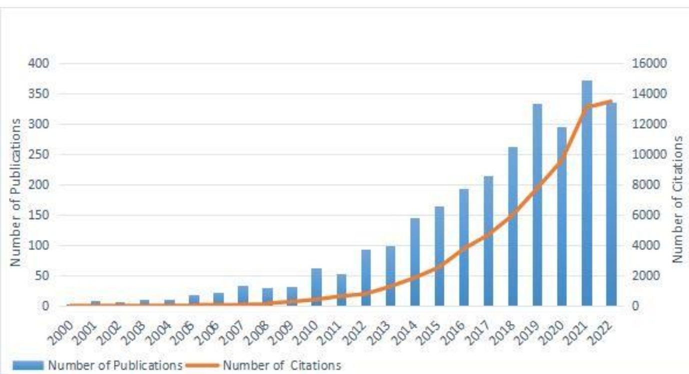

Figure 6. Number of publications, citations from 2000 to 2022 (Created using data from the Web of Science)

The number of papers about building Life Cycle Assessment (LCA) has increased noticeably, as shown in the presentations in Figure 6. This movement underscores the research community's growing interest in and attention to sustainable building practices. The number of publications reached its height in 2021 with 373 publications. The quantity of citations has continuously increased throughout the years (Figure 6).

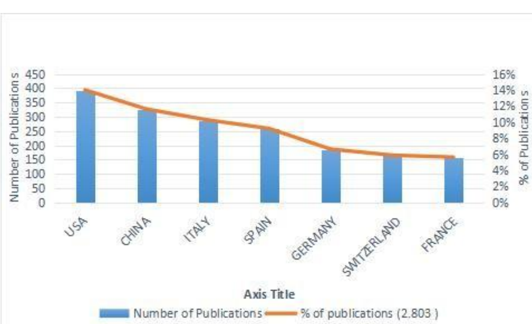

Figure 7. Number of publications for countries citations from 2000 to 2022 (Created using data from the Web of Science)

Figure 7 visually represents the hierarchy among the top seven nations with the most significant publication rates. The United States of America is broadly acknowledged for being at the forefront concerning productivity and the sheer volume of publications it produces. China, on the other hand, holds the second spot in terms of scholarly output. Italy and Spain follow closely behind, occupying the third and fourth positions respectively. The top 10 subject categories and their corresponding number of publications related to building LCA, 2000-2022, are presented in Figure 8. With a record score of 1076, Construction Building Technology is the most popular academic field, closely followed by Environmental Sciences, which has a record score of 1052, and Engineering Civil, which has a record score of 969 (Figure 8).

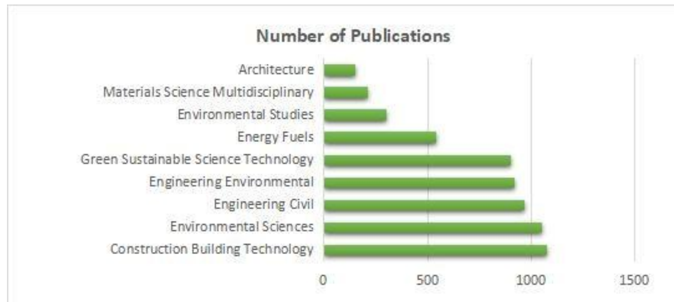

Figure 8. The top 10 subject categories,2000-2022 (Created using data from the Web of Science)

The top 10 subject categories and their corresponding number of publications related to building LCA, 2000-2022, are presented in Figure 8 . With a record score of 1076, Construction Building Technology is the most popular academic field, closely followed by Environmental Sciences, which has a record score of 1052, and Engineering Civil, which has a record score of 969 (Figure 8).

Figure 9. The top 10 journals that publish research related to building life cycle assessment, 2000-2022 (Created using data from the WoS)

Figure 9 lists the top 10 journals publishing research related to building life cycle assessment between 2000 and 2022. The Journal of Cleaner Production tops the index with 266 publications on building LCA, followed by sustainability with 216 publications, and International Life Cycle Assessment with 207 publications. The ranking provides insight into the most prominent academic publications in this field, highlighting the leading sources of research and knowledge development (Figure 9).

Discussion

The increasing number of studies being conducted in this field suggests that LCA is being acknowledged as an effective tool for estimating the sustainability of structures during each phase of their existence. Based on the various studies mentioned, building performance's effect on the environment is a big consideration in the building sector. LCA provides a basis for thoroughly evaluating the environmental impacts of each phase in the life cycle of a building, from construction to operational energy use and eventual demolition. Additionally, the studies conclude that architectural issues such as building ages, orientation, and window-wall ratio could affect the performance of buildings towards their environmental aspect. Overall, the studies demonstrate how critical it is to prioritize environmental implementation throughout the layout and installation of buildings and use LCA to evaluate the environmental impacts throughout a structure's lifetime. The energy analysis investigations specifically emphasize LCA and embodied energy and demonstrate various energy examination methodologies in the built environment. These studies emphasize the necessity of considering buildings' embodied energy and operational phase. It also emphasizes the capacity to implement energy-saving strategies and sustainable design standards that reduce energy consumption and, consequently, lessen greenhouse gas emissions. Several of these studies also demonstrate the international scope of research in this area, including countries such as Australia, China, Italy, Portugal, Thailand, and the United States. These conclusions are of great guiding significance to the development and building of energy conservation and environmental protection buildings, and the evaluation may be mainly oriented to building materials when the research is deepened. LCA's of various building materials have been conducted, such as ceramic and marble tiles, cement, steel, aluminum, concrete, glass, bricks, and insulating boards made from kenaf fiber and timber. The results of all these studies suggest that, indeed, the integration of recyclability and reusability in the materials employed may lead to a significant reduction in the environmental impacts as well as embodied energy. The findings prove helpful in material selection for use in new modern constructions and highlight the environmental requirements. When replacement, in the case of older buildings, is required, the replacement now matches the modern-day environmental needs. In conclusion, building material assessment should be one of the priorities in sustainable construction, and LCA can provide significant data that act as useful tools for you to make decisions to wisely select the best materials. The approach employs the complete set of indicators effectively and efficiently with an entire overview of the sustainability of the building that may guide future activities or assist in accountability and complying with targets linked with environmental management and sustainable development. Several integrated approaches and models are mentioned, such as LCGCA, the combined consideration of the LCAeLEED model, R-LCIA, and LCCE. Machine learning (ML) has also been identified as having the potential to significantly contribute to reducing impacts. The study presents the significance of the native point about developing sustainability assessment in terms of numerous aspects across life cycle stages for buildings. The results of this study are a strong indication that LCA is very important for the establishment and implementation of sustainable construction methods. Life cycle assessment is a necessary tool for proper decision-making of sustainability in construction sectors, which in turn is achieved through the full life cycle of the building. The findings demonstrate that using LCA is a method for the identification of the best choices for the selection of construction materials, design, and the operation of surfaces and buildings.

Conclusion and Recommendations

The construction industry, which is an essential participant in environmental degradation, has therefore been experiencing an increase in eco-friendly methods in response to environmental issues. Sustainable practice becomes vital today, as this is one of the ways for the industry to solve environmental issues with the help of energy efficiency, resource conservation, and the reduction of harmful emissions. The most vital element of the sustainable building approach is the use of a holistic method that integrates the entire life cycle of a component or system. Life cycle assessment is a multi-perspective evaluation of building construction, operation, and maintenance life cycles to determine their respective environmental impacts. This presents developers, designers, and policymakers with valuable information that helps in identifying improvements to make the decision process more sustainable. LCA allows the comparison of different architectural and construction choices with regard to their environmental impact. This approach is aimed at selecting the most sustainable alternatives while setting the stage for the development of environmentally friendly practices. An extensive literature review was carried out to provide a full overview of the use of LCA in the property construction sectors. It provided synthesized information on the progress of knowledge regarding the application and feasibility of these methods, specifically within property-building areas, including research studies conducted so far. This systematic investigation aims to provide a comprehensive and up-to-date outline of LCA utilization in the building sector. The study has thoroughly examined and combined the current knowledge about utilizing LCA in the construction sector. To sum up, the literature study has shown that much research is being conducted on using LCA in the construction industry. Also, the findings in this research indicate that publications and citations concerning the life cycle assessment of buildings have been rising at a constant rate throughout the years. The results show a significant interest in promoting sustainable building practices, conducting environmental impact analysis, emphasizing the energy efficiency of buildings, and the building materials assessment. The present study discusses the significance of looking into building performance in relation to environmental impact on the building construction sector. LCA has been applied to estimate a number of various cases of environmental impacts related to building activities like construction, operation, and demolition. The studies underscore the critical environmental consequences of electricity consumption and construction material production. Moreover, these works identify that the assessment of the sustainability of buildings must be holistic in approach, and hence, a range of integrated techniques and models has been proposed. LCA can contribute to material-based information for material selection, and in support of this, research finds that selecting recyclable and reusable materials can help in cutting down the environmental impact and embodied energy of building materials. This study supports the case for environmental performance to be prioritized in building design and construction. Therefore, LCA plays a crucial role in the establishment of sustainable construction methods. LCA offers an extensive examination of the environmental impacts of structures that highlights potential areas for enhancement in material selection, building design, and functioning aspects. LCA is among the major tools used to try to meet the set goals related to sustainability. The outputs of conducting a life cycle assessment could help in better resource utilization, reduction of waste material, or increase of sustainability environmentally. LCA implementation during decision-making can also assist in making better and more rational decisions to reduce environmental burdens as well as sustainability decisions. In conclusion, LCA is the technique that helps get a detailed view of all the environmental impacts associated with industrial processes and products. Therefore, sustainability is considered an essential part of efforts.

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