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Comparative Analysis of Scientific Papers on LCA Applied to Nanoparticulated Building Materials

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Abstract: Nanomaterials have emerged as versatile components revolutionizing diverse industries, yet their environmental and health impacts remain insufficiently explored. This paper delves into the latent hazards accompanying their evolution and integration, particularly within the construction sector. It addresses the critical gap in assessing their life-cycle impacts, emphasizing the necessity of explicit reporting on nanoparticle emissions. Employing a Life Cycle Assessment (LCA) approach, this research evaluates the sustainability of nanomaterial applications. The absence of nanoparticle-specific data in existing product databases underscores the need for comprehensive life-cycle emission reporting. Since direct impact calculations remain unfeasible, incorporating predicted emissions and risk assessments into LCA studies is recommended. This study advocates for incorporating nanoparticle risk evaluations into LCA methodologies to enhance sustainability and environmental safety. By prioritizing precise emission data and predictive risk analysis, it advances nanomaterial environmental assessments, contributing to the responsible implementation of nanomaterials in construction.

Keywords: Life Cycle Assessment; building materials; nanoparticles; sustainability; construction; sustainable development

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1. Introduction

The correlation between the construction industry and its environmental impact has been extensively debated. Even though it is vital to fostering social and economic development, its processes have significant environmental effects [1].

The industry comprises several stages, including mining, manufacturing, construction, use, and demolition, with each phase having significant adverse impacts on the environment, consuming substantial amounts of energy, and emitting considerable amounts of pollutants [1].

Energy usage occurs directly during the construction, utilization, and demolition processes, as well as indirectly through the embodied energy involved in manufacturing building materials [2]. In accordance with a report from the United Nations and other recent studies, the construction industry stands out as the primary contributor to greenhouse gas emissions, comprising almost 38% of the total global CO_2 emissions [3]. Breaking down this statistic, buildings contribute to approximately 27% of CO_2 emissions associated with operational energy, excluding materials [4–6]. Recent data indicate that construction activity in most major economies has returned to pre-pandemic levels. Consequently, the

energy demand in buildings has increased by approximately 4% relative to the previous period, marking the largest annual rise observed in the past decade [4].

As stated above, the importance of buildings in climate change mitigation stems from their considerable impact on greenhouse gas emissions and the rising domestic energy demand at the global level [7]. Although the building sector's pivotal role in addressing climate change challenges is widely recognized, only minimal structural modifications have been implemented to reduce energy consumption or lower emissions [4,8–10]. While there has been some progress in policy development, the absence of meaningful structural changes underscores the widening gap between the sector's climate performance and the required decarbonization pathway [4].

In an effort to reduce the environmental impacts of the industry, the focus of research and development has shifted toward the use of sustainable building materials as a means of achieving sustainable construction. In light of escalating concerns regarding environmental issues and the mounting pressure from governmental entities and environmental advocates, numerous studies have focused on minimizing energy consumption and the environmental footprint of buildings [11].

For certain industrial applications and consumer products, manufactured nanomaterials offer numerous advantages over conventional options, such as minimizing the need for raw materials and/or energy [12,13].

Nanomaterials (NMs) are defined as any intentionally manufactured material containing particles that, for 50% or more of the particles in the number size distribution, have one or more external dimensions in the size range of at least 1 to 100 nm. These materials gained significance when researchers discovered that particle size can impact the physiochemical properties of a substance, such as its optical characteristics [14].

Despite their promising applications, many uncertainties remain regarding MNMs, especially with regard to their potential environmental and human health risks if they are released into the environment. MNMs can be released during any phase of their life cycle, from the production and manufacture of nanoproducts to their use and eventual disposal. A thorough understanding of these potential releases throughout the entire life cycle, as well as their potential consequences, is essential for ensuring the safe and sustainable utilization of these materials. Therefore, life-cycle thinking is essential for effectively mitigating the potential consequences of MNM releases [13,15].

The LCA method is widely recognized as a systematic tool for evaluating the environmental impact of building materials and construction processes. It quantifies material flows and analyses their interactions with the environment, while also identifying opportunities for environmental improvements [16–18]. As an internationally recognized framework applied across a wide range of fields, including construction, LCA enhances sustainability by providing insights into the environmental footprint of products and processes [19,20].

By integrating LCA, designers, engineers, and decision-makers can make informed choices, considering environmental impacts rather than relying solely on initial costs [21]. LCA assesses the environmental footprint of a product from cradle to grave, categorizing emissions into various impact categories, such as climate change, acidification, eutrophication, resource consumption, and toxicity [22–24]. As shown in Figure 1, LCA is an iterative process and involves four main steps [24]:

1. Goal and scope definition: The goal and scope definition phase outlines the purpose of the study, the rationale for conducting the analysis, and other technical aspects, such as the impact categories, the system boundary (both geographical and temporal), and the functional unit for the analysis, are determined [18,25].
2. Inventory analysis: The second phase, referred to as the Life Cycle Inventory (LCI), entails gathering data or compiling an inventory of all inputs (such as raw materials

and energy) and outputs (such as waste and emissions) across the product's entire life cycle (Figure 2). The data collected are essential for calculating the environmental impact of the product. This inventory analysis phase is both the most iterative and time-intensive step in the LCA process [18,25].

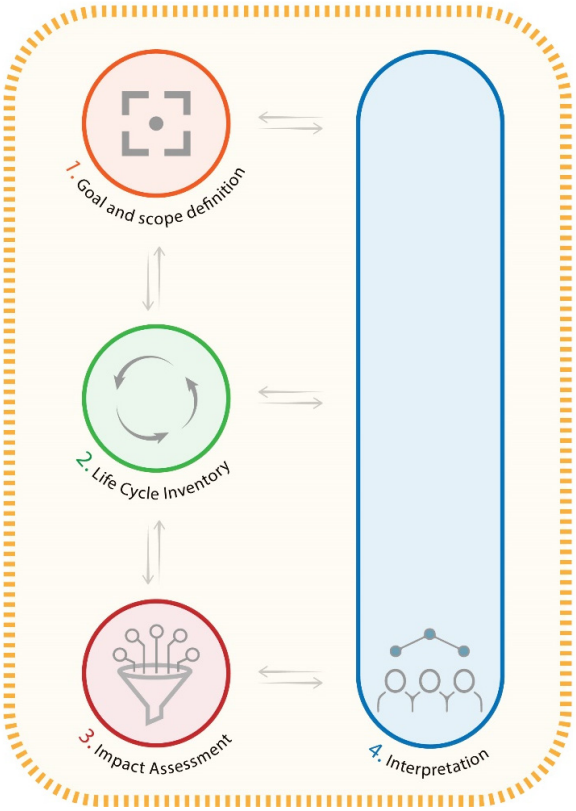


Figure 1. LCA framework.

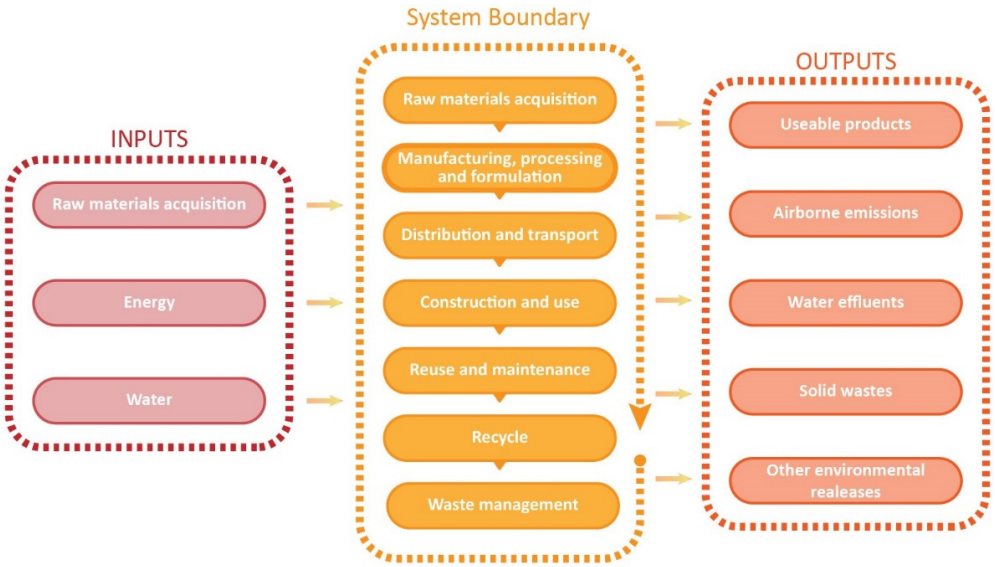


Figure 2. Inputs and outputs over a product's life cycle.

3. Impact Assessment: This third phase, also known as the Life Cycle Impact Assessment (LCIA), focuses on evaluating the potential environmental consequences originating from the inputs and outputs quantified during the inventory analysis phase, as well as the estimated resource usage. The impact assessment is achieved by translating the

environmental loads into environmental impacts, such as climate change, acidification, eutrophication, etc. [18,25].

4. Interpretation: In the interpretation step, the focus is on identifying major issues, interpreting the results to draw conclusions, addressing limitations, and providing recommendations from the impact assessment, ensuring that the conclusions are thoroughly substantiated. The standard ISO 14044 provides several checks for data quality and procedures followed during the LCA study to support the conclusions [18,25].

In 1993, a standardization initiative was launched under the International Organization for Standardization (ISO) to improve the interpretation of LCA results. This initiative produced a unified framework and fundamental principles, resulting in standards such as ISO 14040 (1997) for LCIA, ISO 14041 (1998) for Life Cycle Inventory analysis, and ISO 14043 (2000) for interpretation. Presently, the ISO 14044 standard, which was developed in 2006 alongside an updated version of the foundational LCA standard ISO 14040:2006, establishes the standards for LCA [23,26,27].

Undertaking an LCA study for a product or a service involves exploring industrial systems and collecting and analyzing vast amounts of environmental data, which can be an overwhelming task. However, with growing awareness of environmental concerns, a quantitative assessment of impacts has become increasingly relevant [21]. These environmental concerns can be related to long-term issues such as resource consumption or direct impacts on human health and the natural environment. Clearly, there is a need for structured environmental assessment tools, and LCA is one such tool that is widely acknowledged and accepted for evaluating the environmental impact of products and services.

Through LCA studies, a detailed assessment of the environmental impacts associated with particular products across their entire value chain can be obtained [21,28]. In industry, LCA can be applied at the initial stages of product design to identify and possibly mitigate environmental impacts by designing for recycling and/or selecting the materials with lower environmental impact. LCA is also used to communicate the environmental profile of a product to different stakeholders and consumers [19–21].

As industries increasingly adopt LCA, its application has also expanded to advanced materials, including nanoparticulated building materials. With the rapid development and growing use of these materials, assessing their environmental impact through LCA is essential. Addressing this challenge requires a systematic review of the existing scientific literature. Therefore, the following methodology, as outlined in Figure 3, was designed to structure this comparative analysis. This approach addresses key research questions and challenges unfolding at distinct stages throughout the research, ensuring a comprehensive evaluation of LCA's applications in this emerging field.

The methodology in divided into two parts: the introduction section, where the basics concepts are introduced, and the current challenges section, where the main hurdles to address during the investigation are exposed. Both sections are included within the blue dashed circles.

Thus, the steps to take are the following:

1. Identification of the problem and contextualization of basic concepts, thoroughly explained in the introduction, to know the origin and the theoretical foundations of nanomaterials, as well as the environmental impact of the current production system. This section will answer two main questions: what nanomaterials are, and how a sustainable building is designed, which are both closely related.
2. Identification of the advantages of LCA, defining its different phases and the challenges in its applicability to nanoparticles. This section will address the primary question of how to evaluate and quantify the environmental impact of a building.

3. Identification of the advantages that nanoproducts offer in the construction sector, with the purpose of distinguishing materials with specific and advanced properties, thus identifying their environmental and health impacts during the construction process to select the construction materials that incorporate nanoparticles and generate the least impact. This will allow for informed decision-making and the prioritization of materials that align with sustainability and health considerations.

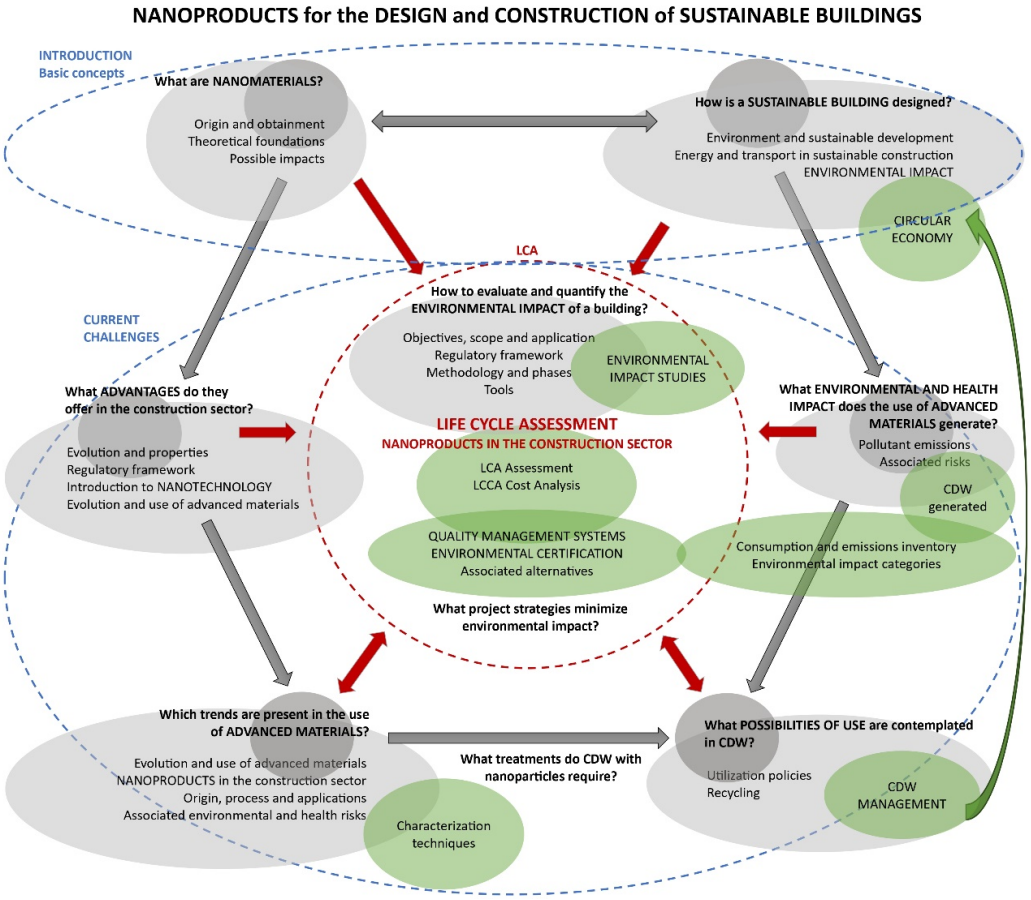


Figure 3. Methodology.

This section will address the following questions: what advantages advanced materials offer in the construction sector, which trends are present in their use, and what environmental and health impacts their use generates.

Along with these aforementioned queries, the diagram presents the conceptual and procedural contents to tackle, encompassed in grey and green circles, respectively, in order to obtain a complete response.

The previous points will conclude in the application of an LCA of nanoproducts applied in the construction sector, gathering the conclusions from each phase, and thereby accomplishing the research objective. Following this, each stage of the proposed methodology will be developed.

A thorough approach, such as LCA, offers valuable insights into potential environmental concerns and contributes to ensuring the sustainability of nanomaterials. The starting point of this research was identifying nanoparticles and nanoparticle-containing materials used in the construction industry. Following that, standards for impact categories on LCAs and existing LCA databases in the construction sector were identified. Moreover, in order to perform an overall comparative analysis across reviewed papers, a few indicators compiling impact categories were summarized. Finally, the comparative analysis revolves

around the following four aspects: LCA methodology in use, analyzed impact categories, site boundaries, and scope of assessment.

2. Materials and Methods

Sustainable construction processes have been of key importance to the construction industry for the last two decades. The environmental impacts that may result from such processes are of equal importance to the decision-makers. This has led to the quest for the application of life-cycle thinking, with a view to reusing and recycling materials [29]. Building materials play a crucial role in the construction industry, and the use of sustainable building materials has become increasingly important in recent years.

2.1. Life-Cycle Assessment Fundamentals

As previously mentioned, LCA is a widely recognized method to evaluate the environmental burdens associated with a product, service, or process throughout its life cycle, from raw material extraction to final disposal, from cradle to grave, in order to help consumers make environmentally beneficial decisions. The primary objectives of LCA are to quantify or characterize all inputs and outputs throughout the product's life cycle, specify the potential environmental impacts, and explore alternative strategies to minimize these impacts [30].

In recent years, many countries have introduced normative criteria for the LCA of building materials to regulate their environmental impact. The development of normative criteria can vary depending on factors such as national policies, regulations, and industry practices. Therefore, it is important to conduct comparative studies to understand the differences and similarities in the normative criteria for LCA of building materials in different countries [31].

While ISO standards provide a general framework for LCA, the specific methodology for calculating environmental impacts is not outlined. Depending on the nature of the research, various techniques can be selected, each defined by its environmental mechanisms, as detailed in ISO 14044:2006, which pertains to environmental management, LCA, and the associated requirements and guidelines [31].

Numerous research endeavors have substantiated that LCA studies conducted on complete buildings serve as invaluable instruments for scrutinizing architectural concepts. These studies not only provide a thorough understanding of the environmental consequences related to a building but also play a pivotal role in informing decision-making processes geared towards minimizing ecological footprints. Nevertheless, the LCA methodology has some inherent limitations, requiring careful interpretation and application of the results.

In the first place, one challenge is the difficulty of comparing cases, due to unique characteristics such as specific layouts, climate conditions, comfort requirements, and local regulations. A second limitation is the variability in estimated building lifespans. These limitations can be partially addressed by expressing annual impacts per square meter of useful floor space or per person. However, differences in system boundaries, assumptions, detail levels, and LCIA methodologies may still persist [32,33].

As a simplified representation of reality, LCA inherently relies on assumptions that may introduce uncertainties at various levels, such as within the model structure, scenario projections, and parameter uncertainties [32,33]. Processing the first two aspects statistically is challenging and is typically omitted from analyses, but the third can be analyzed due to the presence of data quality indicators for materials and processes in the databases. Parameter uncertainty is often exacerbated by data gaps, leading to less accurate data utilization. Addressing the variability and stochastic errors of the figures improves reliability, although

interpretation must rely on probabilistic methods. Despite being less conventional, these methods provide valuable conclusions [31].

Throughout the building life cycle, the use phase is the most impactful in terms of environmental burdens, particularly due to its intensive energy consumption. The estimations for this phase rely on average values derived from societal data. The unpredictability of individual inhabitants' behavior presents a challenge when assessing the reliability of conclusions regarding energy consumption. This unpredictability limits the practical relevance of LCA, regardless of the accuracy of its calculations. Research has shown that many efficiency improvements do not achieve the predicted reductions in energy consumption. The decreased cost of energy services resulting from these improvements typically leads to increased usage. Known as the rebound effect, this psychological behavior has not yet been considered [31,32]. While a stochastic approach incorporating real data could help address this problem to some extent, rebound effects are unavoidable. Economic savings often lead to increased spending in other areas, unrelated to buildings but still environmentally impactful. Moreover, the variability in user behavior and consumption habits, often shaped by regional differences, adds another layer of complexity [20,31].

One of the drawbacks of the current application of LCA in the construction sector is often characterized by an isolated approach to environmental challenges. The analysis often focuses on identifying environmental optima without integrating other critical aspects, such as quality, energy efficiency, structural integrity, or aesthetic considerations. Additionally, although it has been scarcely investigated yet, design has a significant influence on the environmental profile, often having a greater impact than purely technological innovations. Furthermore, financial feasibility is rarely addressed, despite the availability of tools such as life-cycle costing. Despite the development of new regulations and frameworks aimed at evaluating all aspects of sustainability, their implementation remains limited [31].

However, despite certain limitations, LCA remains a highly effective and science-based tool for assessing environmental impacts.

2.2. Nanoproducts in the Construction Sector

In recent years, nanotechnology has gained widespread recognition as a prominent concept, thanks to remarkable advancements in the science, engineering, and commercial sectors, including the construction sector [14,34]. The unique physical and chemical properties exhibited at the nanoscale provide remarkable advancements in areas such as (photo)catalysis, thermal and electrical conductivity, mechanical durability, and optical performance. These advancements enable diverse applications, ranging from catalysts and sensors to electronic devices, energy storage systems, and advanced mechanical materials [34].

As a recognized prominent field of study since the last century, nanotechnology focuses on nanoparticles, which are broadly defined as a diverse category of materials featuring particulate substances with at least one dimension below 100 nm [14]. Additionally, as stated in Commission Recommendation 2011/696/EU, which proposes a revision of the definition of nanomaterials to align with current scientific advancements and practical experience, nanomaterials are defined as "a natural, incidental or manufactured material consisting of solid particles that are present, either on their own or as identifiable constituent particles in aggregates or agglomerates, and where 50% or more of these particles in the number-based size distribution fulfil at least one of the following conditions [35]:

a. one or more external dimensions of the particle are in the size range 1 nm to 100 nm.
b. the particle has an elongated shape, such as a rod, fibre, or tube, where two external dimensions are smaller than 1 nm and the other dimension is larger than 100 nm.

c. the particle has a plate-like shape, where one external dimension is smaller than 1 nm and the other dimensions are larger than 100 nm" [35].

Particles with at least two orthogonal external dimensions larger than 100 µm are excluded from the determination of the number-based particle size distribution. Similarly, materials with a specific surface area by volume below 6 m^2/cm^3 do not qualify as nanomaterials [35].

For the purposes of this classification, the following definitions are provided for reference:

a. "Particle" refers to a minute portion of matter with distinct physical boundaries, excluding single molecules.
b. "Aggregate" describes a particle composed of strongly bound or fused smaller particles.
c. "Agglomerate" pertains to a group of loosely bound particles or aggregates, with an external surface area comparable to the sum of its individual components [35].

Unlike simple molecules, nanoparticles have a complex structure comprising three layers:

a. The surface layer, which is the outermost layer and can be functionalized with various small molecules, metal ions, surfactants, or polymers.
b. The shell layer, a material chemically distinct from the core.
c. The core, which is the innermost layer and serves as the central structure of the NP, generally identified as the nanoparticle itself [36].

NPs can be broadly classified into various types based on their morphology, size, and chemical properties [14]. The US Environmental Agency has classified nanomaterials into four types according to their main components: carbon-based nanomaterials, metal-based nanomaterials, dendrimers, and composite nanomaterials. Carbon-based NPs include fullerenes, which have a spherical or ellipsoidal structure, and nanotubes, which are cylindrical. Metal-based NPs cover a range of materials, including quantum dots, gold and silver nanoparticles, and metal oxides such as titanium dioxide. Lastly, dendrimers are polymeric nanoscale particles composed of branched units, characterized by numerous terminal groups on their surface and internal cavities capable of encapsulating other molecules. Composite nanomaterials combine different types of nanoparticles or combine nanoparticles with larger materials [37].

Furthermore, according to the origin of the nanomaterials, they are classified as follows: natural, being produced by trees, plants, volcanoes, or marine species; incidental, when they arise during combustion in vehicles and industrial processes; and artificial, the most common type, produced by two manufacturing processes (top–down/bottom–up). On the one hand, top–down techniques consist of the division of macroscopic material or a group of solid materials until reaching nanometric size. Physical methods, such as grinding or wear, chemical methods, and the volatilization of a solid followed by the condensation of the volatilized components, are utilized until a series of assemblies are obtained, which are precisely controlled until reaching the desired size. On the other hand, bottom–up techniques consist of the manufacture of nanoparticles with the capacity to self-assemble or self-organize, facilitated by the condensation of atoms or molecular entities either in a gas phase or in solution [37].

Due to their exceptional and advantageous properties, including enhanced structural characteristics, functional coatings, and high-resolution sensing and actuating devices, nanoparticles are increasingly applied in various sectors of the construction industry. Nanomaterials in construction, often referred to as manufactured nanomaterials, are those that have undergone manufacturing processes [14,34].

Nanomaterials are incorporated into various construction products, especially in surface coatings, concrete, window glass, insulation, and steel. Furthermore, nanoparticles are gaining popularity in material solutions aimed at the preventive conservation of cultural

heritage. This is attributed to their anti-degradation properties, which facilitate consolidation, anti-fungal, and hydrophobic activity. Relevant reviews on the use of nanomaterials for preserving stone, wooden, or paper cultural heritage have been conducted [38,39]. In Table 1, nanoparticle-containing materials used in the construction industry are identified, defining their properties and applications in the sector.

Table 1. Nanomaterials in construction [34,40,41].

Nanoparticle Type	Material/Application	Expected Benefits
SiO_2 nanoparticles	Concrete Ceramic Windows	Reinforcement in mechanical strength, rapid hydration Coolant; light transmission; fire-resistant Flame-proofing; anti-reflection
TiO_2 nanoparticles	Cement Windows Solar cell	Rapid hydration; increased degree of hydration; self-cleaning Superhydrophilicity; anti-fogging; fouling resistance Non-utility electricity generation
Carbon nanotubes	Concrete Ceramic NEMS/MEMS Solar cell	Mechanical durability, crack prevention Enhanced mechanical and thermal properties Real-time structural health monitoring Effective electron mediation
Fe_2O_3 nanoparticles	Concrete	Increased compressive strength, abrasion-resistant
Cu nanoparticles	Steel	Weldability, corrosion resistance, formability
Ag nanoparticles	Coating/painting	Biocidal activity
Clay nanoparticles	Bricks and mortars	Increased compressive strength and surface roughness
Al_2O_3 nanoparticles	Asphalt, concrete, timber	Increased serviceability
ZnO nanoparticles	Cement	Enhanced performance
$CaCO_3$ nanoparticles	Concrete	Accelerated hydration, increased flowability, and increased compressive strength
MgO nanoparticles	Coating/painting	Energy-saving

Within the European Union, nanomaterials are regulated under the same stringent framework that applies to all chemicals and mixtures: the REACH and CLP regulations. These regulations require the assessment of the hazardous properties of nanoforms and ensure their safe use [42].

For a substance to be legally manufactured or imported in the EU, all chemicals within the scope of REACH must be registered. Depending on the volume placed on the market, manufacturers and/or importers are required to submit data concerning human health, environmental effects, and hazardous nanoforms, along with a life-cycle exposure estimation [42].

The same requirements apply to nanomaterials. When substances are deemed hazardous, the Classification, Labelling, and Packaging Regulation mandates their notification to ECHA and requires proper labelling and packaging, ensuring safe use [42].

Companies must ensure transparency in their REACH registration by clearly demonstrating how the safety of nanoforms has been addressed, including outlining the necessary measures to effectively control potential risks. ECHA guidance documents provide additional support to companies for identifying and reporting the properties of their nanoforms [42].

2.2.1. Environmental Risks Associated

As new materials are developed and brought into use, understanding their potential movement and effects on air, water, soil, and biota becomes essential [34]. Although NMs have many reported benefits in various sectors, there are potential health and environmental hazards associated with their development and application that are not yet fully understood. Nanomaterials are typically produced through bottom–up techniques like physical and chemical vapor deposition and liquid-phase synthesis. These processes require substantial energy and material resources, resulting in pollution through effluents and emissions to air, water, and soil [14].

The integration of manufactured nanomaterials in construction materials can provide significant benefits, yet these may be overshadowed by concerns about their potential to act as harmful environmental pollutants after accidental or incidental release. This reinforces the necessity of conducting proactive risk assessments and establishing regulatory guidelines for the safe use and disposal of MNM-containing products [34].

An unresolved question is whether nano-enabled construction materials can be designed to be "safe" while still exhibiting the properties that make them functional. It is essential to prioritize the adoption of industrial ecology principles and pollution prevention strategies to minimize environmental pollution and the negative effects of MNMs. Some substances can be redesigned to develop safer, more environmentally friendly, and still effective products. Therefore, it is essential to understand the molecular structures and related properties that make nanomaterials harmful, as well as to identify which receptors are most vulnerable [34].

The above emphasizes the necessity of advancing research on safe practices for designing, producing, using, and disposing of materials, while also focusing on recycling, reuse, and remanufacturing strategies that can improve the sustainability of both the nanotechnology and construction industries [34].

2.2.2. Associated Health Risks

For nanotechnology in construction to be environmentally responsible, it is essential to consider both the unintended environmental impacts at each stage of the product's life cycle—including manufacturing, construction, use, demolition, and disposal—and the health effects of MNMs on construction workers and [34].

The use of nanomaterials represents a revolution in improving the performance of products. The mechanical characteristics of materials have increased their properties thanks to the application of nanoparticles and nanocomposites. But at the same rate as the quality of the materials has improved with the application of these nanocomposites, the safety of workers is being greatly compromised. Numerous studies have established that there are proven health risks associated with various manufactured nanomaterials, which, given their size, can interact at the cellular level. Nanomaterials are an invisible threat to workers' health [43].

Despite the advantages that these materials offer, many workers are not aware that they are working with them, and their harmful effects are not yet clear. Table 2 compiles the main health implications of nanoparticle emissions.

Table 2. Health implications of nanoparticle emissions.

Nanoparticle Type	Affected Cell/Organ/System
Silver nanoparticles (Ag NPs)	Immune system Lungs Liver Brain Carcinogenesis
Titanium dioxide (TiO_2)	Vascular system Reproductive organs Fibroblast Inflammation in lungs DNA damage Metabolic changes
Zinc oxide nanoparticles (ZnO NPs)	Carcinogenesis Cell death Cell proliferation
Iron oxide (Fe_3O_4)	Oxidative DNA damage
Copper zinc ferrite ($CuZnFe_2O_4$)	DNA damage Oxidative DNA damage
Carbon nanotubes (CNTs)	DNA damage Oxidative stress
Copper dioxide (CuO)	Inflammation DNA damage
Silica nanoparticles (SiO_2)	Oxidative DNA damage Bronchoalveolar carcinoma

Consequently, air monitoring throughout the manufacturing processes should be performed periodically across the entire operational area. Producing nanomaterials in the required quantities for construction applications entails scaling up the process, which may necessitate new controls and safety protocols. The lack of defined material descriptors presents a significant challenge to the establishment and enforcement of safety and handling protocols. Moreover, certain nanomaterials may take on various forms during their life cycle, which affects the degree of occupational exposure [43].

Due to the lack of comprehensive information on toxicology, health effects, and the effectiveness of safety measures such as ventilation and personal protective equipment, the safety and health risks of working with nanomaterials remain poorly understood. Additionally, there is a lack of Occupational Exposure Limits (OELs) and a definition of the appropriate metric for determining exposure to nanomaterials [43]. It is therefore necessary for users to be aware of the potential negative effects on workers' health and the environment, and to take measures to control the risk.

According to the analysis conducted in the previous sections, the environmental and health effects of nanoparticles are primarily driven by the unique reactivity that arises at the nanoscale, due to their small size and high surface area. These properties enable nanoparticles to interact directly with biological membranes, cells, and tissues, leading to the generation of reactive oxygen species, which is the main mechanism behind oxidative stress, cytotoxicity, and DNA damage. The effects vary significantly across different

nanoparticles, due to factors such as particle composition, size, and the environmental conditions to which they are exposed. For example, certain nanoparticles, such as TiO_2, become more toxic under UV light, while others, such as CuO, consistently show strong reactivity regardless of the external conditions. The variation in effects also depends on how easily these particles are absorbed by organisms, their ability to accumulate in tissues, and their persistence in the environment. Additionally, differences in toxicity between species, as well as variations in exposure routes (inhalation, ingestion, or dermal contact), contribute to the broad spectrum of observed impacts. Ultimately, the environmental impact and human health effects of nanoparticles are determined by a complex interplay of factors, including the physicochemical properties of the nanoparticles, the characteristics of the exposed organisms, and the specific environmental conditions.

Nevertheless, the lack of standardized nanoparticle impact assessments in current LCA methodologies highlights the need for a more refined evaluation framework. Developing such a framework would require combining insights from multiple fields to create an LCA methodology that more accurately reflects the environmental and human health risks associated with nanomaterials. This would improve decision-making for the sustainable development of nanotechnology. Moreover, establishing standardized impact assessment tools for nanoparticles could ensure more consistent evaluations across the nanotechnology sector, facilitating regulatory processes and enabling industry stakeholders to make informed, responsible choices.

3. Results and Discussion

3.1. Environmental and Methodological Challenges in the LCA of Nanomaterials

Although NMs have demonstrated numerous benefits across various sectors, there are potential health and environmental risks associated with their development and application that are not yet fully understood. As previously mentioned, nanomaterials are typically produced through bottom–up techniques such as physical and chemical vapor deposition or liquid-phase synthesis. These processes require substantial energy and material resources, resulting in pollution through effluents and emissions to air, water, and soil [14].

While extensive research on nanomaterials has concentrated on their distinct functionalities in different applications, it has often neglected the potential environmental consequences throughout their life cycle. This lack of attention raises concerns about the sustainability of NM pathways and their potential role in environmental degradation [14,34]. Consequently, LCA provides a comprehensive framework for evaluating these impacts and promoting the environmental sustainability of nanomaterials [44].

Nanoparticles are usually incorporated into composite elements, and a single type of nanoparticle may be associated with multiple materials to form different composite configurations. Furthermore, the properties of nanoparticles depend largely on their shape and surface characteristics, resulting in behaviors that differ significantly from those of the corresponding bulk materials [14]. Consequently, their behavior, whether released into the environment or absorbed by biological systems, differs significantly from that of bulk material analogs. Due to their size and shape, these particles react with the environment and tissues differently to the corresponding bulk substance, and currently these processes have not been adequately addressed by scientific research [14]. Consequently, today, it is challenging to create risk assessment frameworks for many types of nanoparticles [45].

Recent studies have investigated the LCA of nanomaterials and identified three principal methodological challenges: The first challenge is the limited use of a functional unit that adequately reflects the unique and enhanced functionalities of nanomaterials. The second challenge concerns the lack of available Life Cycle Inventory (LCI) data in nanomaterial production, where manufacturers may withhold critical material and energy input

information due to commercial confidentiality. Finally, the third challenge is the absence of appropriate characterization methods for released nanomaterials, which are essential for LCIA [44].

Despite these constraints, the application of LCA to nanomaterials has gained traction and has already been applied to a wide range of products including nanoparticles [13,44]. Consequently, several guidance documents have been developed to support its implementation. A notable example is the guidance for applying LCA to nanomaterials developed by REACHnano Consortium. This document provides practical recommendations for manufacturers and downstream users of engineered nanomaterials to carry out comprehensive risk and environmental assessments that encompass all life cycles and considerations of nanomaterials [46].

In the following subsections, the main methodological steps involved in conducting an LCA for nanomaterials are presented. These are structured in accordance with established best practices, while addressing the specific scientific and technical challenges inherent to the assessment of nanomaterials.

3.2. Definition of Objectives and Scope of the Study

In the realm of nanomaterials' LCA, it is advisable to consider the following recommendations to ensure a comprehensive and insightful analysis:

Firstly, considering that the discharge and emission of nanoparticles predominantly occur during the utilization phase and at the conclusion of a product's life cycle, contingent upon the management practices of nanoproducts, the potential impacts linked to each nanoproduct's life cycle will be specific. Consequently, it is advisable that LCA studies concentrate on evaluating nanoproducts rather than isolating their focus on nanoparticles [46].

Secondly, nanomaterials offer the prospect of enhanced products with improved or novel functionalities. Frequently, the utilization of nanomaterials facilitates a decrease in energy consumption, raw material utilization, and emissions. In light of these considerations, it becomes crucial to establish a suitable functional unit that comprehensively encompasses these advantages [46].

Thirdly, environmental and toxicological ramifications associated with nanomaterials manifest across all stages of their life cycle. Consequently, it is recommended to broaden the scope of LCA studies for these products to encompass a "cradle to grave" perspective [46].

Lastly, in instances where there is limited information available for specific stages, it is recommended to undertake a sensitivity analysis by considering various scenarios. This approach ensures a more comprehensive understanding and robust evaluation within the context of the LCA [46].

3.3. Development of an Inventory of Consumption and Emissions

Currently, LCI assessments for nanomaterials confront several noteworthy challenges, as outlined in the following [46].

Information pertaining to nanomaterials is notably absent from existing LCA databases. Consequently, addressing these data gaps is imperative, and it is crucial to meticulously fill in these voids, particularly for each individual study. Failure to do so may compromise the integrity of the study outcomes, rendering them incomplete and not reflective of the entire process [46]. It is recommended to prioritize the incorporation of data derived from real measures of the assessed processes for greater accuracy and reliability.

Moreover, the data pertaining to the production of nanomaterials are frequently classified as confidential. Compounded by the rapidly evolving nature of this technological domain, the scarcity of available data necessitates making estimations for certain processes. Consequently, this introduces a level of uncertainty that must be meticulously assessed [5].

Indeed, a meticulous study of each evaluated nanoparticle synthesis method is essential for acquiring accurate information on consumption and emission flows. In the process of estimation, it becomes imperative to scrutinize and discuss diverse scenarios to ensure a comprehensive assessment [46].

Additionally, concerning the emissions of nanoparticles, a pivotal phase often involves the integration of nanoparticles in powder form into the material. In such instances, it is imperative to incorporate the exposure of workers to nanoparticle emissions during the production process into the LCA study. This consideration adds a crucial dimension to the overall assessment, encompassing occupational health and safety concerns in the production phase [46].

Furthermore, it is crucial to emphasize that LCA studies for nanomaterials must encompass all stages throughout the product's life cycle, adhering to a comprehensive "cradle to grave" approach [46].

The collection of information for each process is imperative, necessitating a meticulous approach to gather as many data as possible pertaining to the assessed process. The objective is to compile a comprehensive set of emissions data that encompass the entire life-cycle stages of the process, ensuring that emissions of nanoparticles are thoroughly included in the resulting LCI. This inclusive methodology ensures a thorough examination of the environmental and toxicological impacts associated with nanomaterials, providing a holistic understanding of their life-cycle implications [46].

Moreover, the assessment of uncertainty is a critical aspect of the analysis. It is imperative to systematically evaluate and quantify uncertainties inherent in the data, methodologies, and assumptions employed throughout the LCA for nanomaterials [13]. This process ensures a comprehensive understanding of the reliability and robustness of the study results, thereby enhancing the credibility of the assessment.

Lastly, it is recommended to systematically collect information concerning emissions by utilizing structured templates. Employing such templates facilitates a standardized and organized approach to data gathering, ensuring consistency and comprehensiveness in capturing relevant details about emissions during the life cycle of nanomaterials [13]. This method enhances the efficiency and accuracy of the information-gathering process for a more rigorous LCA.

In intricate detail, the following specific data elements should be meticulously addressed during the comprehensive assessment of nanomaterials within an LCA [13]:

- Production stage:
    a. Inputs and outputs during the production stage; consumption- and emission-associated.
    b. Emissions of nanoparticles during the production stage; exposure of workers.
    c. Releases during the production stage; compartment of the emission.
    d. Transformation of the particle after the emission.
- Use stage:
    a. Lifespan and services obtained from the product.
    b. Inputs and outputs produced during use; maintenance, cleaning, consumption, and emissions associated with use.
    c. Emissions of nanoparticles during the use stage; exposure of workers.
    d. Releases during the production stage; compartment of the emission. Transformation of the particles after the emission.
    e. Possibility of nanoparticle emissions during use. Environmental compartment of the emission. Transformation of the particle after the emission.
- End-of-life stage:

a. Characteristics of nanoproduct waste generated at the end-of-life stage.
b. Treatment and final disposal of nanoproduct waste.
c. Recycling: Type of recycling process. Emissions of nanoparticles during recycling. Quantity of nanoparticles in recycled products.
d. Disposed to landfill: Degradation or transformation of nanoproducts. Environmental compartment for the final fate of nanoproduct waste.
e. Incineration: Transformation of nanoparticles after incineration. Nanoparticles included in resulting ashes. Environmental compartment for the final fate of nanoproducts included in the resulting ashes.

3.4. Selection and Quantification of Environmental Impact Categories

As mentioned earlier, it is crucial to note that emissions of nanoparticles have implications for both the human toxicity and environmental toxicity impact categories. It is noteworthy that existing impact calculation methods do not adequately address these specific categories when it comes to nanoparticle emissions. Specialized and nuanced approaches may be required to accurately assess and quantify the impacts associated with the release of nanoparticles on human and environmental toxicity within the context of LCA [34,43].

Considering the aforementioned challenges and considerations regarding the LCA of nanomaterials, the following recommendations are proposed to improve the effectiveness and accuracy of such assessments in this phase.

Primarily, it is recommended to employ impact assessment methods endorsed at the European level, specifically those outlined in the International Reference Life Cycle Data System (ILCD) handbook. Utilizing these established methods ensures a standardized and comprehensive approach to evaluating the environmental and toxicological impacts associated with nanomaterials throughout their life cycle.

Moreover, incorporating impact categories pertinent to nanoparticles—such as, notably, Human Toxicity and Ecosystems Toxicity—is recommended. By doing so, the LCA can more effectively capture and assess the specific risks and effects associated with nanomaterials, offering a more nuanced understanding of their environmental and health implications [47,48].

Finally, it is advised to derive characterization factors for assessed emissions by employing prospective approaches grounded in consensus models that align with the specific characteristics of releases and the fate of the corresponding processes. This method ensures a robust and forward-looking analysis, enhancing the accuracy of characterizing the environmental and toxicological impacts associated with nanomaterial emissions in LCA studies [47].

To achieve this, it is recommended to collaborate with a multidisciplinary panel of experts specializing in risk assessment. In situations where calculating characterization factors may be challenging, adopting a worst-case approach is advised. This involves utilizing characterization factors for analogous substances, such as the corresponding bulk substance, while taking into consideration potential variations in the final fate behavior. This pragmatic approach helps ensure a thorough evaluation of environmental and toxicological impacts in instances where precise characterization factors are not readily available [46,47].

As highlighted earlier, neither method incorporates defined fluxes or characterization factors for the assessment of nanoparticle-specific damage. Consequently, it becomes imperative to conduct a targeted evaluation of this risk. The pertinent impact categories related to nanoparticles encompass ecotoxicity for aquatic fresh water, human toxicity, and particulate matter [46–48].

3.5. Interpretation of Results

This phase involves a comprehensive review of both inventory data and impact scores, forming the basis for drawing conclusions from the study. It encompasses critical elements such as sensitivity analysis and the assessment of uncertainties, ensuring a robust and informed finalization of the LCA.

Indeed, as highlighted earlier, LCA studies on nanomaterials inherently confront a significant level of uncertainty. Therefore, it is imperative that all utilized data and sources of uncertainty be meticulously documented. In the current landscape, extracting reliable and robust results from LCA studies on nanoparticles holds substantial value, not only for informing immediate decision-making but also for contributing to the enhancement of existing methods and databases in the broader scientific community [47]. This commitment to transparency and the acknowledgment of uncertainties contribute to the continuous improvement of methodologies and the advancement of knowledge in the field of nanomaterials. During this final phase of the study, the following recommendations are proposed to ensure a thorough and effective conclusion.

Initially, to enhance the rigor and reliability of the study, it is advisable to subject it to an external critical evaluation conducted by a panel of experts with proficiency in both LCA methodologies and nanotechnology. This external review aims to ensure an impartial and thorough examination of the study's approach, data sources, and findings, leveraging the expertise of individuals who are well versed in the nuances of LCA and nanotechnology [13,47].

Additionally, conducting an uncertainty analysis is essential to gauge the robustness of the results and is recommended as a pivotal step in the study. This analysis provides valuable insights into the reliability of the findings, offering a comprehensive understanding of the potential variations and limitations associated with the data and methodologies employed in the LCA [47].

Furthermore, utilizing the outcomes derived from the LCA studies to augment existing inventory data within databases and contributing to the refinement of impact characterization methods are highly recommended. This proactive approach not only enhances the comprehensiveness of available data but also plays a crucial role in advancing the accuracy and effectiveness of methodologies used for assessing environmental and toxicological impacts associated with nanomaterials [13,47].

If a characterization factor is unavailable for the assessed emissions, it is essential to integrate a custom predictive scenario designed explicitly for the evaluated nanomaterial. This scenario should encompass the following components [47]:

- Measurement of the releases of nanoparticles over the entire life cycle of the product, from its inception to its disposal (cradle to grave).
- Identification of the specific environmental compartments associated with each instance of nanoparticle release.
- Anticipation of the long-term destiny of the released nanoparticles, encompassing an understanding of the transformations that these nanoparticles undergo in the environment following emission.
- Evaluation of the toxicity impact on both humans and the environment resulting from the emissions of produced nanoparticles.

4. Conclusions

The gap in understanding of the fate and impacts of nanoparticle emissions presents significant challenges for evaluating their environmental and health implications. Current LCA methodologies are limited due to the lack of specific nanoparticle data, which hinders comprehensive risk assessment. To address this, it is essential to adopt alternative methods

that can evaluate the full range of impacts associated with nanoparticles, focusing on both emissions and their broader environmental and health effects.

A crucial step is to ensure explicit reporting of nanoparticle emissions across the entire life cycle of nanoproducts. As current Life Cycle Inventory (LCI) databases lack nanoparticle-specific data, a more detailed and tailored approach to data reporting is necessary to improve LCA's accuracy. Additionally, integrating predictive modeling and risk assessments into LCA studies can provide a more comprehensive evaluation of potential risks, especially when precise data are unavailable.

Efforts like the EU-funded Eunon Nano Data project are already working to fill these gaps by providing accessible information on nanoparticle emissions, environmental fate, and risk assessments [49]. Such initiatives are crucial for supporting informed decision-making in industries utilizing nanomaterials.

This study contributes valuable data to the construction industry, focusing on environmental health and safety, and supports the responsible integration of nanoparticles into construction materials. This promotes sustainable practices while mitigating potential risks. However, the variability in manufacturing processes for different nanoparticle types means that their impacts can vary widely. LCA provides a structured approach for decision-makers to balance the benefits and risks of nanomaterials in material selection.

To produce reliable LCA results, it is essential to use high-quality data and rigorous methodologies. Understanding comparative Process Contribution Ratings (c-PCRs) within Environmental Product Declarations (EPDs) also aids in identifying opportunities to reduce environmental impacts. The LCA data in these declarations should not only be made publicly available but should also be strategically used to pinpoint areas for improvement.

In conclusion, while LCA is promising for assessing the sustainability of nanomaterials, there remains considerable scope for further research. Future studies should analyze the entire life cycle of nano-modified materials, incorporating a range of nanomaterials as modifiers, to rigorously assess their sustainability. Addressing these gaps will be key to ensuring the responsible and sustainable integration of nanomaterials in industries such as construction.

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