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Review

Nanomaterials Applied in the Construction Sector: Environmental, Human Health, and Economic Indicators

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Abstract: Over the past two decades, the application of nanostructured materials in construction, such as concrete, paint, coatings, glass, renders, plasters, thermal insulation, steel, and even sensors, has become increasingly prevalent. However, previous studies and reports have raised concerns about the ecotoxicity and long-term impact of nanomaterials on human health and the environment. National and international legislation and regulations are struggling to keep up with the rapid development of nanomaterials, taking into account their unique characteristics and essential requirements for application and commercialization. This paper, based on existing standards for conventional materials and bibliometric networks of papers focused on nanomaterials, conducts a critical review and proposes relevant indicators for the application of nanomaterials in the construction sector. These indicators should be mandatory and are divided into environmental, human health, and economic perspectives, providing a risk assessment framework for applying nanomaterial-based constructive solutions oriented to environmental, social, and economic sustainability.

Keywords: nanomaterials; environment; human health; economic; impacts; risk; indicators

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1. Introduction

Advanced nanomaterials (NMs) have been widely used in several sectors, from medicine to electronics, aerospace, biotechnology, textiles, agriculture, and, most importantly, in the construction sector [1]. In fact, the nanomaterial market in the European Union (EU) increased from EUR 2.6 billion and 63.3 kilotons in 2016 to EUR 5.2 billion and 141 kilotons in 2020. Metal oxides were the most widely used NMs (88.4% by volume), followed by nanoclays (10.6%), carbon-based NMs (0.5%), dendrimers (0.4%), nanocellulose (0.2%), and metals (0.1%) [2].

Nanomaterials are considered relevant for future employment, financial growth, and technical innovation, as they are materials with high potential to replace (or be added to) conventional materials and chemicals [3–6]. In fact, nanotechnology has been identified as a Key Enabling Technology, providing the basis for further innovation and new products [7].

The International Organization for Standardization [8] defines a nanomaterial (i.e., size ranges from 1 to 100 nm) as a "material with any external dimensions in the nanoscale or having internal structure or surface structure in the nanoscale" [1,8–10]. NMs have been designed with various sizes, shapes, crystalline structures, and surface functionalization. Synthesis methods, either bottom-up or top-down, involve physical, mechanical, and chemical processes [11], which can result in different material properties, sizes, and yields [11,12]. The chemistry and physics of nano-sized construction materials differ from ordinary materials [13] owing to quantum effects and a high surface-to-volume ratio [13]. In fact, the increased surface area of nanostructured materials enhances the availability and thus the reactivity of atoms for interaction with environmental factors or other materials [10,14]. This capability enables the development of multifunctional materials, such as natural hydraulic lime mortar with titanium dioxide (TiO_2) addition, incorporating heterogeneous photocatalysis functionality. Such materials can be utilized to combat atmospheric pollution and contribute to the creation of more durable and low-maintenance building facades [15].

Despite the fine-tuning of synthesis methods in recent years, the production and integration of NMs remain more expensive compared to conventional materials. In certain cases, the high cost hinders their widespread application, as in the case of aerogel-based insulation materials [3]. Furthermore, the necessity for upscaling industrial production often poses challenges to the commercialization of nanomaterials [16]. Nevertheless, the growing demand and the optimization of production processes have spurred an increased search for nano-enabled materials [16–21].

Within this context, EU regulations such as REACH and CLP are challenged to keep up with the rapid development of nanomaterials [22]. Previous studies [23,24] examining the physical and chemical properties, environmental results, and ecotoxicology of nanoparticles used in construction materials (e.g., nanoclays, aluminum oxide, titanium dioxide, silver nanoparticles, and carbon nanotubes) have concluded that the 2015 OECD report [25] on manufactured nanomaterials lacks comprehensive data and presents an incomplete portfolio [24]. In fact, there is limited literature available that explores the relationship between the physical–chemical properties and toxicity of NMs, which could facilitate the grouping of surface modifications [14]. Considering the current literature gap and the main sustainability pillars, the main objective of this article is to discuss and identify environmental, social (in this case human health), and economic indicators, comparing EU standards for general/conventional materials with a literature review for nanomaterials. The proposed indicators should be mandatory for nanomaterials and can also be employed to achieve a more accurate assessment of sustainability [19,26,27]. The systematic incorporation of these specific indicators for nanomaterials in construction will enable the evaluation of the long-term effects of nanomaterials on the environment and human health, as well as on overall costs during the life cycle (LCA), from manufacturing to end-of-life processes.

2. Nanomaterials in the Construction Sector

2.1. Overview

Several applications of nanomaterials can be identified in the construction sector, e.g., concrete, mortars and renders, thermal insulation materials, glass windows, solar panels, paintings, and coatings, among others [14]. Nanotechnology can either improve the properties of the final materials or extend their service life and life cycle [16,18]. Utilizing nanomaterials as construction materials has the potential to improve their inherent properties or introduce additional functionalities. For instance, the incorporation of SiO_2 nanoparticles has been reported as an effective method for reinforced concrete [16,18]. Similarly, the inclusion of metal oxides, such as iron, titanium, aluminum, and zinc, in paints and surface coatings can serve to prevent corrosion and resist dirt accumulation [11]. The addition of small percentages of TiO_2 and ZnO has also been used as UV filters in glass [2] or as photocatalytic additives [15]. Nanoclays have been introduced into cementitious matrixes for pervious concrete pavement [28]. Nanostructured (calcium, barium, or magnesium) hydroxides and alkoxides have been used for the conservation of porous calcareous materials, such as mural paintings, limestone, and historical mortars [29]. Carbon-based NMs (CNs) and graphene-based materials (GO) improve serviceability, including high thermal and electrical conductivity, proper elasticity and flexibility, low thermal expansion coefficient, and electron field emitter capabilities [30–32].

Table 1 summarizes several types of nanomaterials, as well as their compositions, applications, and functionalities, based on the literature review.

Table 1. Types, applications, and functions in the construction sector of several nanomaterials.

Nanomaterial	Synthesis or Production Method	Applications	Functionality/Improvement	References
Nanosilica	Sol-gel	Mortars, concrete	Abrasion resistance; Acceleration on cement hydration; Concrete-to-steel bonding; Improved freeze–thaw resistance; Mechanical improvement; Pozzolanic activity; Paste–aggregate bonding; Permeability reduction	[33–42]
		Coatings	Corrosion inhibition efficiency	[43]
		Roads, footpaths	Mechanical improvement	[44,45]
Iron oxide	Mechanical milling; electro explosion; laser ablation; sol-gel; atomic condensation; template-assisted	Mortars, concrete	Electrical conductivity; Enhanced ductility; Mechanical improvement; Piezoresistive property; Permeability reduction; Self-sensing	[46–49]
Nanosilver	Electro-explosion	Paints, coatings	Biocidal activity	[50–53]
Titanium dioxide	Sol-gel; chemical vapor deposition; template-assisted	Mortars, concrete	Abrasion resistance; Acceleration on cement hydration; Increased durability; Mechanical improvement; Self-cleaning	[48,54,55]
		Glass	Anti-fogging; Fouling resistance; Self-cleaning	[56]
		Paints, coatings	Antimicrobial; Anti-pollution; Air-purifying surfaces; Coolant; Hydrophobic; UV resistance	[57,58]
Calcium hydroxide and alkoxides	Colloidal; microemulsion; micelle-assisted; solvothermal reaction; sol-gel	Wall paintings	Biocidal activity; De-acidification; Protection of cultural heritage	[59–65]
		Limestone		
		Lime-based mortars		
		Renders and plaster		[66,67]
		Cellulose-based materials (canvas/wood)		[68]
Magnesium or barium hydroxides	Colloidal; sol solutions	Wall paintings, Lime-based mortars	Biocidal activity; Protection of cultural heritage	[69,70]
Nanoclay	Mechanical milling	Mortars, concrete	Mechanical improvement	[71]
Carbon nanotubes	Mechanical milling; laser ablation; chemical vapor deposition; template-assisted	Mortars, concrete	Crack prevention; Concrete-to-steel bonding; Decreased porosity; Mechanical improvement; Self-sensing	[38,40,72]
		Sensors	Health monitoring in construction	[16]
		Solar cells	Electrical conductivity	[73]
Graphene oxide	Mechanical milling; chemical vapor deposition	Mortars, concrete	Mechanical improvement	[74–77]
		Paints, coatings	Biocidal activity; Corrosion inhibition efficiency	[78,79]

Table 1. *Cont.*

Nanomaterial	Synthesis or Production Method	Applications	Functionality/Improvement	References
Phase change materials	Sol-gel	Building components, thermal insulation materials, wallboards	Thermal resistance	[80–82]
Silica aerogel	Sol-gel	Mortars, concrete, renders	Decreased thermal conductivity	[83–85]
		Blanket	Acoustic insulation; Thermal resistance	[86–88]
		Glazing, window	Dispersion of the incident light	[82,89–91]
Nano copper	Colloidal methods	Steel mesh	Corrosion inhibition efficiency; Formability; Weldability	[92]
Aluminum oxide	Sol-gel	Asphalt concrete	Increased serviceability	[93]
		Concrete	Acceleration on cement hydration; Mechanical improvement	[33,42,48]

Although NMs can improve the properties and performance of construction materials, several NMs are not easily available due to restrictions on their use and commercialization, as well as to the availability of raw materials and, as previously stated, to high production costs [11]. Furthermore, nanoparticles (NPs) can have a low compatibility with some construction materials and are prone to aggregation phenomena, which hamper homogeneous dispersion [94–97]. Another relevant challenge is related to their potential toxicity and thus the risk to human health and the environment [98–104].

2.2. Impact on Human Health and on the Environment

The increasing use of NMs also leads to an increased production of waste and residues, with the relevant exposure of operators in the building sector [105]. Approximately 60% of nanomaterials are used in medical–pharmaceutical or industrial applications (e.g., in the textile and electronics industries) with several industrial processes which can lead to waste streams resulting from the cleaning of production chambers [106]. Thus, an in-depth understanding of human and environmental exposure and NPs' toxicological effects is a necessary step to assess environmental and health impacts [107–109].

Exposure to NPs is often associated with inhalation or absorption through skin contact. Although the dosages required to induce these effects are rather high, toxicological health risks include lung damage, adverse effects on the immune system, disorders related to oxidative stress, and diseases such as cancer, as well as DNA damage, and changes in cell growth and renewal, processes which are essential for healthy organs and tumor prevention [3,30,110]. Therefore, there are numerous recommendations for handling NMs during their production, transport, application, and end-of-life disposal process, including the use of gloves, coveralls, air filter masks, and safety goggles [105,111].

Hallock et al. [112] reported that ultrafine particles (<100 nm) of TiO_2, Al_2O_3, and carbon black NPs demonstrated higher toxicity than fine particles (<2.5 µm). The nano-size may act as an amplifier of the effects, resulting from a higher reactivity or dissolution rate, although the nanostructure is not a sufficient descriptor to correlate with toxicity in the aquatic medium. In fact, the potential toxic effects of NPs depend on their physicochemical characteristics (size, shape, composition, surface functional groups, and surface charges) and can be influenced by the surrounding matrix [113,114]. Therefore, the environmental impact of these NPs is contingent upon characteristics such as decreased size, which enables their entry into the cellular environment and interaction with proteins. The shape of the particle also influences the cellular uptake mechanism, and the presence of a coating can prevent the leaching of toxic metal ions [114].

Figure 1 shows the systemization of NMs' impact on the environment and of human exposure during the life cycle stages. This release can occur during all stages of the life cycle: production, manufacturing, use of nanoproducts, and their disposal and recycling [23,102,115,116]. Most NMs are generally released to the environment through wastewater treatment plants, recycling processes (e.g., including dismantling, shredding, and thermal processes) [117], waste incineration, and landfills. As an example, solid sludge from pilot wastewater treatment plants can retain more than 80% of some types of NMs, while the remaining 20% cannot be generally processed and are therefore discharged to surface waters [118]. Furthermore, NPs' durability can be affected by weathering, with substantial modifications throughout their life cycle [113], and, when released into the environment, can undergo complex biological, physical, or chemical reactions and modifications, depending also on the specific characteristics of the materials and the environmental conditions [119].

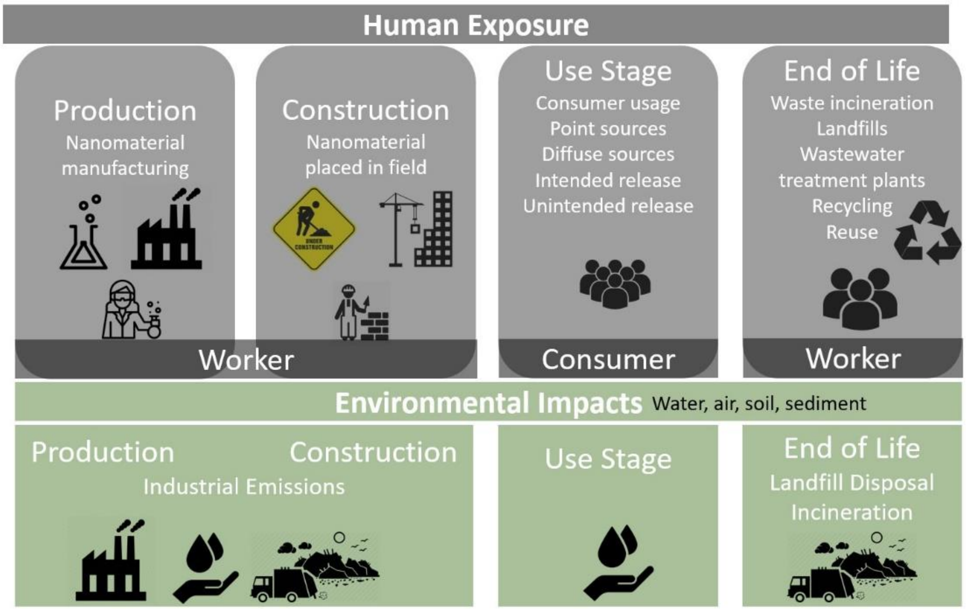

Figure 1. Nanomaterials' influence on the environment and human health during the life cycle stages.

Wind and runoff can transport NPs from solid waste or accidental spills to other locations and water bodies, contaminating surface water and soil and lixiviating into groundwater [120]. Wastewater effluents and direct discharges can disperse particles into waterways, and, if hydraulically connected to saturated zones, transport them to aquifers. Furthermore, NPs can be released into the atmosphere and form aerosol suspensions, and thus dust, during the shredding processes of synesthetic or metallic composite materials [118] or during exposure to fire or combustion [3].

Waste containing NMs, such as concrete (which may contain CNTs, SiO_2, Fe_2O_3), ceramics (SiO_2, CNTs), antibacterial coatings and paints (AgNPs), self-cleaning coatings (TiO_2), window coatings (SiO_2), and improved anticorrosive steel (CuNPs), are currently disposed of along with conventional waste without specific precautions or treatment [118]. Silica-based aerogels are barely considered, as landfill is a common end-of-life destination [121]. It is worth noting that the emission of NMs into the air, water, and soil is strictly dependent on how landfills are organized and practiced, although the mechanisms and quantification of NMs' release into the environment are not yet completely understood [118]. Thermal recycling/degradation and waste-to-energy combustion can be considered as two alternatives to landfill processes [122,123].

The toxicity of NMs can also be related to their cost. In fact, Gkika et al. [103] analyzed the impact of the materials' cost by considering their toxicity, concluding that NMs with a low cost and low toxicity (e.g., titanium carbonitride and aluminum, multi-walled carbon nanotubes) have significant applicability and thus diffusion on a wider scale. Conversely, the use of NMs with a high cost and toxicity (e.g., titanium oxide, copper oxide, or even single-walled carbon nanotubes) should be reconsidered [103].

Although the toxicity of NMs presents certain concerns, nanotechnology can also act as an effective approach for environmental remediation [108,109]. In fact, manufactured nanomaterials (MNMs) can decompose, eliminate, or neutralize harmful substances present in contaminated environments [108]. Furthermore, NMs can be designed to reduce interactions with the cell surface, e.g., by having a negative surface charge (electrostatic stabilization of NMs), or using ligands (e.g., polyethylene glycol) or morphologies that reduce protein binding. Less toxic elements can be used in NMs that also use shell materials (e.g., TiO_2 with a silica or aluminum oxide coating [124]), which decrease the interaction with the core or the environment, or by introducing a chelating agent (which reduces the cytotoxicity of nanostructured metals) or antioxidant molecules (which prevent the degradation of the NMs) [125]. Finally, new green synthesis routes have been fine-tuned in recent years for different types of nanomaterials, including metal-oxide-based, inert-metal-based, carbon-based, and composite-based NPs [126].

3. Keyword Bibliometric Network: Nanomaterials

A literature review was carried out using the Scopus database, inserting the keywords "environment", "nanomaterial or nanomaterials", "impact", and "risk", and evaluating the bibliometric networks using the software VOSViewer version 1.6.20. In the timespan 2011–2022, in the areas of research of engineering and construction, 357 published documents were collected: 322 peer-reviewed articles and 35 conference papers, as shown in the bibliometric network in Figure 2 and the evolution of papers in Figure 3 (dark blue column).

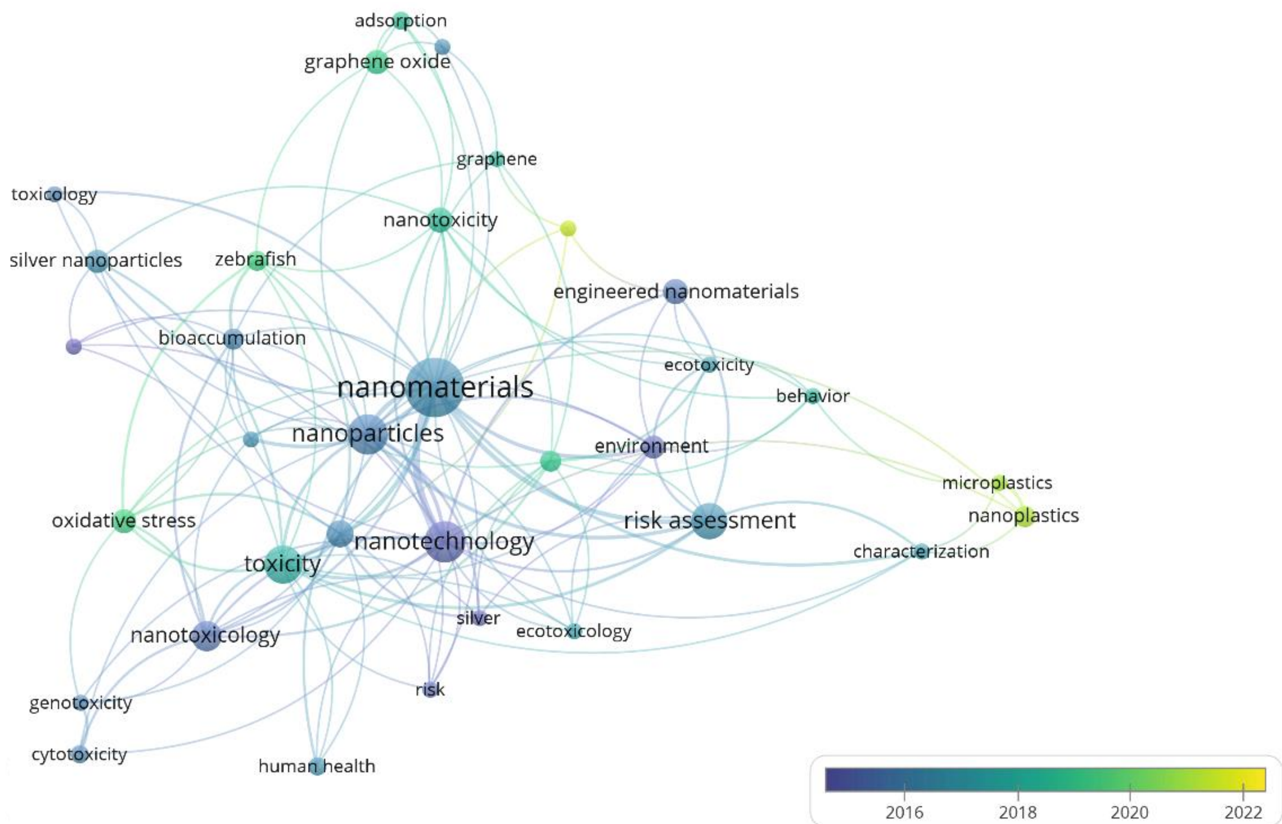

Figure 2. Keyword bibliometric network of nanomaterials and their impact on human health and the environment.

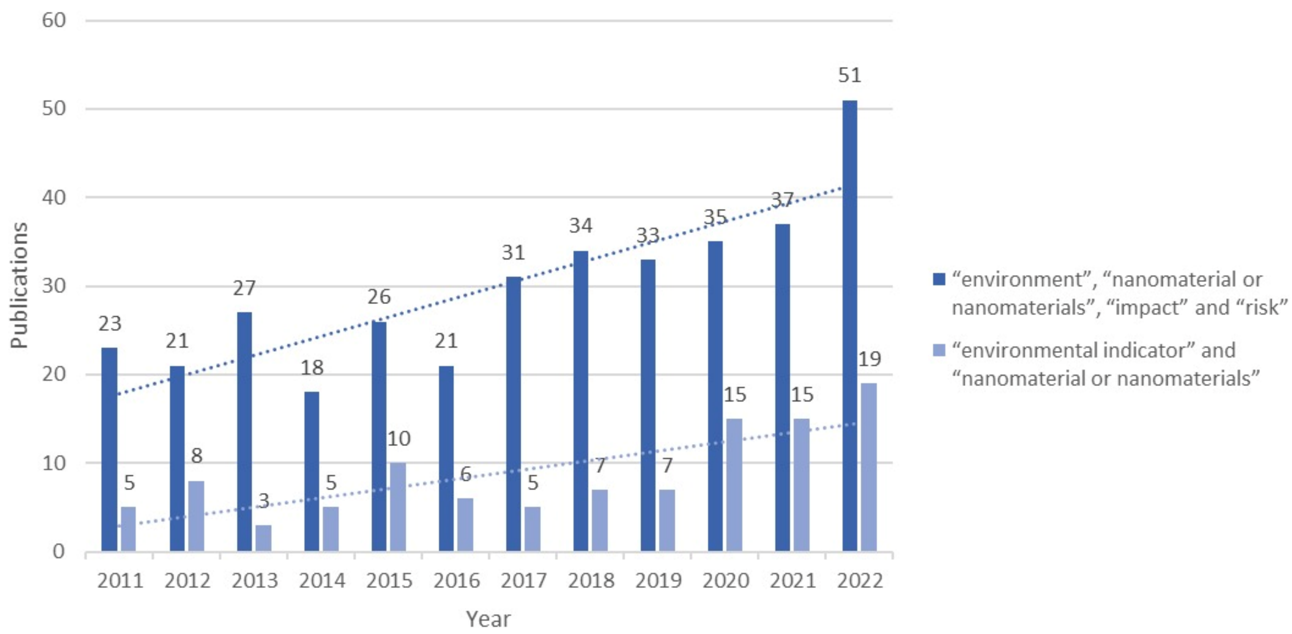

Figure 3. Evolution of peer-reviewed papers (number per year) on nanomaterials and their impact on human health and the environment (timespan 2011–2022).

It is worth noting that certain groups of NMs, such as AgNPs and TiO_2 or GO nanoparticles, are strictly associated with keywords such as environmental impact, toxicity, human risk, risk assessment, and economic impact. As shown in Figure 3, the interest in nanomaterials has significantly increased over the last decade (+35% of peer-reviewed articles focused on this topic). Furthermore, in studies of NMs, health and environmental issues are often related to the risk assessment of NPs during their life cycle.

Searching the Scopus database between 2011 and 2022 with the keywords "environmental indicator" and "nanomaterial or nanomaterials", a total of 105 documents (97 articles and 8 conference papers) were found, most of them related to environmental science, chemistry, and medicine; the number of publications has almost doubled in the last three years compared to previous years (Figure 3, light blue column). Using the same timeline metrics and database, we found 18 documents, including 14 articles and 4 conference papers, by adding the keywords "economic indicator". This suggests the importance of addressing the balance between environmental and economic impacts.

It is worth mentioning that, despite recent progress, an interdisciplinary and reliable methodology, fulfilling EU regulatory requirements intended to manage environmental and health risks (e.g., REACH (chemicals) regulation 1907/2006, biocidal products regulation 528/2012, cosmetic products regulation 1223/2009, novel food regulation 2015/2283, food additives regulation 1333/2008, and the medical devices regulation proposal COM 542/2012), has been proposed but has not been widely accepted [22,127]. Moreover, specific proposals or standards aimed at correlating physicochemical properties and ecotoxicity are often lacking.

4. Critical Discussion of Environmental and Economic Indicators

Based on the previous extensive literature review (Section 3), as well as considering European standards (EN15804:2012+A2:2019 [128]; EN15643 [129] and international databases for conventional materials, the most relevant contributions of NMs to environmental, social, and economic impacts were identified. Based on these data, environmental, human health, and economic indicators were proposed and are summarized in Table 2.

Table 2. Environmental, human health, and economic indicators proposed for nanomaterials.

	Impact Category	Indicator Name	Indicators Acronym	Functional Unit	Referenced * NM	Refs.
Environmental and human health indicators	Depletion of abiotic resources, minerals, and metals	Abiotic depletion potential for non-fossil resources	ADP-minerals and metals	kg Sb eq.	AqNPs CuO TiO_2 CNTs	[130–141]
	Depletion of abiotic resources, fossil fuels	Abiotic depletion for fossil resources potential	ADP-fossil	MJ		
	Acidification	Acidification potential, accumulated exceedance	AP	mol H+ eq.		
	Ozone depletion	Depletion potential of the stratospheric ozone layer	ODP	kg CFC-11 eq.		
	Photochemical ozone formation	Formation potential of tropospheric ozone	POCP	kg NMVOC eq.		
	Water use	Water (user) deprivation potential, deprivation weighted water consumption	WDP	m^3 world eq. deprived		
	Climate change, total	Global warming potential, total	GWP-total	kg CO_2 eq.		
	Climate change, fossil	Global warming potential, fossil	GWP-fossil	kg CO_2 eq.		
	Particulate matter emissions	Potential incidence of disease due to PM emissions	PM	Disease incidence		
	Ecotoxicity (freshwater)	Potential comparative toxic unit for ecosystems	ETP-fw	CTUe		
	Human toxicity, cancer effects	Potential comparative toxic unit for humans	HTP-c	CTUh		
	Human toxicity, non-cancer effects	Potential comparative toxic unit for humans	HTP-nc	CTUh		
	Land-use-related impacts/Soil quality	Potential soil quality index	SQP	(dimensionless)		
Economic indicators	Cost	Initial costs	IC	EUR/m^2 or EUR/unit	TiO_2 CuO Silica aerogel CNTs Fe_2O_3 GO	[103,142–144]
		Operation and maintenance	OM			
		Repair	RE			
		Replacement	REP			
		Deconstruction	DE			
		Transport	T	EUR/m^2		
		End of life	EoL	EUR/m^2		
		Waste processing for re-use, recovery, and/or recycling	W	EUR/m^2		
		Recycling	REC	EUR/m^2		

* Referenced NMs—includes the NMs that were most cited in the literature review for those impacts.

Concerning the economic indicators, it is suggested to include not only the initial costs of the different NMs (in EUR/unit), but also further costs related to operation and maintenance (repair or replacement) and eventual deconstruction. Additionally, at the end of the life of NMs, costs related to their transport, waste processing for re-use, recovery and/or recycling should also be considered.

When an analysis of the environmental impacts of nanomaterials is carried out, we strongly recommend that the proposed environmental and human health indicators for NMs should be mandatory. In fact, there are significant concerns about the long-term effects on humans, both through inhalation and contact, and on ecosystems, especially for those NMs identified as being more toxic to human health, as in the case of CNTs, TiO_2, AgNPs, and Al_2O_3. In fact, CNTs and TiO_2 nanoparticles are among the most widely studied NMs due to their potential hazardous effects. TiO_2 can cause inflammation, cytotoxicity, and damage to the DNA of mammalian cells due its photoactivity. Cu- and Zn-based NMs can also induce high toxicity, causing cellular toxicity via multiple mechanisms (e.g., the disruption of cell walls, nucleic acid damage, and the release of toxic metal ions) [145].

These relevant environmental indicators for NMs in construction include the potential incidence of disease due to particulate matter emissions, ecotoxicity (potential comparative toxic unit for ecosystems), human toxicity (cancer and non-cancer effects), potential comparative toxic unit for humans, and land-use-related impacts on soil quality.

The proposed NM indicators should also be taken into consideration for the Environmental Product Declarations, which provide life cycle assessment (LCA) impacts per material or categorized product in the construction sector. In fact, it is worth mentioning that the data available for materials or elements containing NMs in their composition are generally insufficient, even when considering large databases for ecological evaluations, as in the case of Ökobaudat [146]. However, there is currently an effort underway to change this reality. Efforts to develop testing guidelines for nanomaterials are ongoing, and the outcomes are becoming increasingly accessible [14].

This clarifies why the most crucial environmental indicators were identified as those related to human health and ecosystems, as these impacts must be prioritized over the economic aspects. These indicators, which identify NMs (e.g., CuO, Al_2O_3, TiO_2, and CNTs used in concrete, asphalt concrete, and steel) with reported high toxicity and which are hazardous for the environment, should be considered with the main focus on particulate matter emissions into the air, potential toxicity for ecosystems and humans, and impacts on soil quality.

It is important to mention that the methods of determination could be adapted. In fact, high values for certain indicators could be related to the high degradation of construction materials in aggressive climate conditions due to a higher release rate of NPs. The detailed methods for the determination of each indicator are not within the scope of this paper.

Concerning the economic indicators, all parameters related to the whole life cycle cost should be considered. In fact, the initial costs of NMs are a critical factor. However, it is important not to neglect the potential benefits of using materials with NMs, such as improved performance and, in some cases, lower maintenance costs and increased durability, especially at optimized levels in cement and concrete composites [147].

The proposed indicators can be relevant for all nanomaterials, although some impacts strictly depend on the type of NM. For instance, silica aerogel can have a high end-of-life cost (when incorporated in thermal insulation materials, mortars, blankets, or windows [148]) due to the large amounts required to improve thermal insulation. Although silica aerogel is not a highly toxic material, it can still have a significant impact when deposited in landfills, which requires an evaluation and quantification of the environmental impact [149,150].

The existent European norms deal with regular building materials [129,151], and intend to achieve environmental, social, and economic sustainability. The proposed indicators for NMs in construction include the relevant environmental, human health, and economic impacts to be evaluated and quantified prior to the introduction of NMs into a constructive element in order to gain an accurate perception of their impact.

5. Conclusions

Nanomaterials have been increasingly used and investigated by the scientific community, leading to a wide range of applications. The number of scientific reports has significantly increased in recent years, with several publications focusing on the synthesis, incorporation, or application of nanomaterials (NMs) in the construction sector. On the other hand, the keyword bibliometric network on NMs indicates that terms such as nanotoxicity, environmental risk, risk assessment, and human health risks are scarce in the literature.

This work intended to address the current concerns, evaluate the sustainability (environmental, social, economic) and viability, and thus contribute to the implementation of regulations on NMs, which are often commercialized and categorized similarly to regular construction materials. Based on an extensive literature review for nanomaterials and European standards for regular building materials, environmental, human health, and economic indicators were proposed as mandatory for nanomaterials to be applied in the construction sector.

A particular focus on toxicity (ecotoxicity and human toxicity), soil impacts (land-use-related impacts/soil quality), and emissions into the air (particulate matter emissions) was identified. The use of these indicators should be considered for nanomaterials such as copper, aluminum oxide, titanium nanoparticles, or carbon nanotubes which have significant levels of toxicity and are widely used in the construction sector.

Regarding the economic indicators, it was concluded that the evaluation of the cost impact throughout the various stages of the whole life cycle is essential, focusing not only on the initial cost but also on optimizing the less economically viable stages. These indicators would be particularly relevant for nanomaterials which are generally incorporated in large quantities (e.g., silica-aerogel in thermal insulation composites) and may cause economic problems during recycling processes. Furthermore, the lack of data on durability and end-of-life processes hinders the applicability on a larger scale of nanomaterials such as carbon nanotubes, iron oxide, and graphene oxide.

These proposed indicators could be a good basis for their integration into a risk assessment framework of nanomaterials to be applied in construction.

Limitations of the proposed indicators can be identified in terms of their applicability to certain nanomaterials, functionalized and designed according to specific applications, presenting different physicochemical properties and thus environmental risks. Although the evaluation of the physicochemical properties of nanomaterials that may affect human health, and aquatic and terrestrial ecotoxicology, has been widely debated, the categorization of a small number of nanomaterial groups was identified, which often resulted in specific tests being waived, creating consistent data gaps.

Further research on the in-service life of constructive solutions with the incorporation of nanomaterials and nanoparticles, as well as on end-of-life processes, is necessary. A proper evaluation of these impacts is critical, especially considering that landfill is a common final destination, by using appropriate methods. A deeper knowledge of toxicity-associated properties for nanomaterials in construction (i.e., size, shape, chemical composition, surface properties, agglomeration and/or aggregation state, and biodegradability) is needed, as well as a hazard ranking for each nanomaterial (e.g., the higher toxicity of nano-ZnO is closely associated with its dissolution into toxic Zn^{2+}, in contrast to insoluble nano-TiO_2 and the nontoxic degradation products of nano-SiO_2). Similarly, when assessing the potential toxicity of nanoparticles in aquatic environments, several critical parameters, e.g., the size, crystal structure, surface charge, morphology, surface coating, presence of co-pollutants in the aquatic environment, duration of exposure, concentration, and any photoactive effects, should be considered.

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