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Review Article

Harnessing Nanomaterials for Sustainable Housing to Mitigate Climate Change Impacts and Reduce Health Risk

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Abstract

This is a review describing the emerging applications of nanomaterials in sustainable housing construction and design, primarily to mitigate climatic and health impacts. As the urbanization process has accelerated globally, and with the onset of climate change, there is an insatiable demand for solutions to present a more sustainable and resilient housing system. Nanomaterials have various potentials in bringing about improved energy efficiency in buildings, enhancing indoor air quality, minimizing resource consumption, and providing enhanced resistance to austere outdoor weather conditions in buildings. This paper reviews current researches on nanomaterials application in construction, assesses the environmental and health implications, and identifies research gaps and future directions in the emerging discipline.

Keywords: Climate; Health; Housing; Nanomaterials; Sustainability; Indoor

Introduction

Rapid urbanization and climate change pose unprecedented challenges to housing sustainability and human health. Over 2019, more than 50% of the human population was considered to be residing in the urban area, and this urban population is expected to keep on growing, more so in those underdeveloped regions [1]. Concurrently, amplified temperatures due to climate change are now giving rise to extreme weather events and increase the possibility of environmental health risks inflicted on densely populated urban settings [2,3]. The pressure is more acute in developing countries such as South Africa, where urbanization increases pressure on the infrastructure, and climate change impacts, with laser-like focus, on the vulnerable population [4,5]. In this setting, conventional materials and construction systems are found wanting when it comes to sustainability goals and therefore call for new methodologies. Nanotechnology-the ability to manipulate matter in the scale of 1-100 nanometers-is a new avenue pointing to housing sustainability. Through nanoscale manipulation, construction materials with properties never seen before can be created and proposed to solve multiple sustainability problems at the same time [6,7]. Focus is on different possible but still-evolving applications of nanomaterials in sustainable housing concerning climate change mitigation and health risk reduction.

Nanomaterials in sustainable construction energy-efficient building envelopes

Nanomaterials may greatly constitute the performance of the building envelope, which is primarily concerned with reducing energy consumption and greenhouse gas emissions for heating and cooling. Some applications shown in Table 1. Nano-insulating materials: Aerogels and other nanoporous materials are thermally insulating materials with properties far better than those of conventional construction materials with thermal conductivities as low as 0.013 W/mK [7,8].

Nanocoatings for glass and facade

Specialized nanocoatings selectively filter solar radiation at different wavelengths while transmitting visible light and blocking infrared heat. Such selectively filtering would reduce cooling loads in warm climates without compromising natural daylighting [9]. In addition, self- cleaning nanocoatings reduce maintenance effort and take advantage of photocatalytic properties to maintain the optical clarity of glazing.

Air purification and quality in indoor environments

Indoor air pollution has become a significant health hazard today in both developed and developing countries, especially with respect to urban areas where the outside air is already compromised [4,16]. Nanomaterials are solutions to the problems.

Building materials	Effects on house sustainability	Nano- technologically enhanced building materials	House sustainability potentials	References
Concrete	They emit approximately 1.6 billion tons of CO_2 (accounting for more than 6.5% of total CO_2 emmisions)	Nano-Silica embedded concrete (SiO_2)	It makes the building more densified and compact. Also enhaces reduction in materials needed for constructions. They are known to be water proof	[10]
		Titanium dioxide nanoparticles embedded photocatalytic self-cleaning concrete	Environmental pollution cleansing, photocatalytic properties, and resistivity to dust accumulation, long term enhancement and sustainability	[10]
Glass	Dirt accumulations, molds exospores accumulations, Unchecked ultra violet rays from the sun.	Nano-glass enhanced with heat-insulating materials	Heat transfer reduction and sustainability boosting via energy demand reduction leading to the cooling of the interiors.	[10]
		Self-cleaning titanium dioxide nanoparticles glass	raindrops containing dirts spilled on the glass surface won't leave a trace of dirt deposition	[10]
		Silica nanoparticles fire-protective glass	Fire resistant	[10]
		Tungsten oxide nanoparticles embedded electrochromic glass	Reduction of sunlight rays by turning into blue colour when electricity of around 3 voltage is applied	[10,11]
Coating and Paints	Emission of volatile organic compounds, Environmentally Persistent Free Radicals (EPFR)	Zinc Oxide self- cleaning enamel paint	Self-cleaning properties	[10,12]
		Titanium dioxide nanoparticles coating	self-cleaning and antifouling and properties	[10,13]
		Silver nanoparticles embeded emulsion paint	inhibits the growth of black yeast like Aureobasidium pullulans	[10]
		Silica nano- powder	Anti -aging properties, wear Resistant and toughness improvement	[10,14]
		Hybrid Magnetic Graphene Oxide (HMGO) embedded paint	Antibacterial activities against pathogenic *S. typhimurium*, *Escherichia coli*	[10,15]

Table 1: Importance of Nanomaterials in construction.

Photocatalytic air-purifying systems

Titanium dioxide (TiO2) nanoparticles and other forms of photocatalytic nanomaterials may be blended into paints and coatings for direct use in construction materials to provide catalytic oxidative degradation of VOCs, nitrogen oxides, and other indoor air pollution under light illumination [17]. These systems are relatively passive; require very modest energy input while continuously working for the betterment of indoor air quality.

Antimicrobial surfaces

Silver nanoparticles and copper nanostructures incorporated in surface materials can offer protection against microbial growth thus reducing bioaerosol load and respiratory health risks associated with that [18]. The COVID 19 pandemic in particular has caused a lot of interest in this application since these coatings can probably be helpful in minimizing disease transmission in domestic environments.

Water conservation and management

Water scarcity is being acclaimed as the most quintessential challenge of sustenance in the current times, especially in such areas which have started experiencing shifts in patterns of rainfall due to climate change. All of the above listed materials offer a number of options for improving household water economy:

- **Nanomembrane Filtration Systems:** The newer configurations have the membranes of filtration using various components of nanostructures to serve in the enhanced recovery of greywater and rainwater harvesting system for residential use, so reducing demand on potable water supply [19,20].
- **Superhydrophobic Surfaces:** Once coated with this type of nanoscaled modification, surface actually becomes unbelievable repellent to water; such coatings reduce all that is needed for cleaning and maintaining a building and extend its lifespan at that [21].

Structural performance and resilience

With climate change comes more occurrence and intensity of extreme weather events, which increasingly underscores the importance of resilient buildings. Nanomaterials can contribute to structural performance in the areas of:

- **Nanomodified Concrete:** The combination of carbon nanotubes with nanosilica and several other nanomaterials in concrete composition manifests improvement in mechanical properties while enhancing both compressive and flexural strengths with possibilities of lowering the quantities of cement powder and associated carbon emissions [22,23].
- **Self-Healing Materials:** Nanocapsules containing healing agents can be embedded into concrete and other structural materials, spontaneously repairing microcracks as they form and prolonging the service life of building components [7]. Nanomaterials exhibit vast potential for contribution towards a sustainable housing sector; however, the environmental aspects must be critically explored to attain anything near sustainability.

These include assessing:

Embodied energy and resource efficiency

These involve production methods and materials for the generation of nanomaterials, which vary in intensity of energy consumption. Some nanomaterials are manufactured through energy- demanding processes that may outweigh operational energy-saving benefits [24]. In contrast, methods of green synthesis are such as low-embodied energy processes that use plant-based precursor agents and do not elevate above ambient temperature [19,21]. Furthermore, nanomaterials might slow resource consumption over the lifecycle, extending service life, which enables efficient utilizations of material. Nanomodified forms of concrete have the aforementioned benefits; they provide the same strength with much-reduced cement contents and a much-lower carbon footprint for production [23].

End-of-life management and circularity

Durability and enhanced properties of nanomaterials throw up both opportunities and challenges to circular economy principles in construction. One must also factor in the ways in which nanomaterials could complicate recycling of materials or reuse processes [7]. Studies on recovery and separation techniques for nanomaterials in construction waste streams are still sparse and must be explored in future research.

Environmental health and safety

Nanomaterials possess some of the properties that make them valuable for application in sustainable construction. Therefore, such unique properties could introduce new environmental health risks that would need to be assessed carefully [25]. The risk from exposure to possibly respirable particles, which could be related to occupational or house risks, has to be evaluated due to the potential for risky nanoparticle release during weathering, renovation, or demolition activities. Any of the green synthesis approaches would emit toxicity less than conventional nanomaterials [18,19].

Socio-economic factors involved and challenges in implementation

Moving innovations on nanomaterials from laboratory settings to broader implementation in sustainable housing faces myriad challenges, three of which could be mentioned.

Cost and market adoption

The production price of nanomaterials has generally dropped within the past few years, but price premiums over conventional counterparts prevent their use in most applications, even in affordable housing contexts [26]. He said that extended lifecycles cost analyses at the operational savings stage should be economically viable really only under conditions where initial construction costs are very sensitive [5].

Regulatory frameworks and standards

The entry of nanomaterials into construction has triggered a regime that is not really tuned to the property of the nanomaterials and the possible risks associated with it. Basically, standard testing protocols and performance metrics should be developed for nanomaterial-enhanced building components to certify the quality control and marketability [7].

Nature-based solutions integration

Housing approaches for sustainability are optimally successful when appropriate technological advances are integrated with nature-based solutions. Nanomaterials may interface with green infrastructure solutions, for instance, through nanoparticle trucks for rainwater management or photocatalytic materials combined with vegetation for air pollutant abatement [5,27].

Future directions and opportunities for research

There are just a few other thrusts in research that would require for intensive probing within nanomaterials application in building sustainability.

Multifunctional nanomaterials

The development of nanoconstruction materials for attainment of various concerns regarding sustainability-holding, purification of air, and strength-acts maximizing cost-effectiveness and feasibility of application [7]. Nanomaterials-enabled solutions can be vital in expanding the impacts of seed-related manufacturing processes which include understanding developing countries' low-cost implementations and local resource integration [5]. The development of sensor technologies that can monitor in real time the performance and degradation of nanomaterials over time might yield important knowledge for future optimization and create confidence to address possible long-term risks [23].

Climate adaptation applications

Further investigations on the application of nanomaterials specifically dedicated to increasing the resilience to climatic impacts-extreme heat, flooding, increased storm intensity-demand urgent new research into an area that has focused a lot of its integration efforts into mitigation-dedicated applications, including energy efficiency (Mereotlhe, 2024).

Conclusion

Nanomaterials have tremendous promise for increasing housing sustainability, limiting climate change effects, and reducing health hazards. Applications encompass energy efficiency and indoor air quality improvement, structural resilience, and conservation of resources, creating a multifaceted definition of housing sustainable. The realization of this promise will depend on overcoming hurdles related to environmental impacts, economics, regulatory frameworks, and other barriers to implementation. Future research must mesh the development of innovative multifunctional nanomaterials with particular relevant contexts to improve lifecycle performance and integrate nanomaterial innovations with complementary sustainable design strategies. These measures together will add a most significant contribution to the urgent global concern of creating housing that is more sustainable, healthier, and resilient against impacts of climate change.

Authors Contribution

The authors contributed equally to this work.

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Conflict of Interest

The authors declare no conflicts of interest.

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