

Harnessing the Potential of Nano-Smart Materials in Building Design: A Systematic Review on User Well-Being

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Abstract

The integration of nano-smart materials into building design is transforming the construction industry by providing innovative solutions for creating sustainable, efficient, and health-promoting environments. Key nano-smart materials, including self-healing concrete, thermochromic windows, and piezoelectric sensors, have significant potential to enhance building performance and occupant well-being. This systematic review evaluates the effectiveness of nano-smart materials in the design of army rehabilitation centers, with a focus on improving user well-being in Abuja, Nigeria. A comprehensive search of major databases identified 25 studies that met the inclusion criteria. The findings indicate that the strategic use of nano-smart materials can substantially enhance user well-being, reduce energy consumption, and improve building sustainability. This review discusses the benefits and limitations of these materials in the context of army rehabilitation center design and highlights areas for future research. Overall, the study provides valuable insights for architects, designers, policymakers, and healthcare professionals aiming to develop innovative, evidence-based rehabilitation facilities that prioritize user well-being.

Keywords: Nanotechnology, Rehabilitation Design, Army Rehabilitation Centers, User well-being.

Introduction

The construction sector plays a crucial role in developing and maintaining modern infrastructure and is currently undergoing significant transformation to address challenges related to resource efficiency, sustainability, cost-effectiveness, and structural performance (Azeem et al., 2020; Balasubramanian et al., 2021; Fei et al., 2021). Historically, the industry has relied on traditional materials such as concrete, steel, and timber, focusing primarily on incremental improvements to enhance durability and reduce environmental impact (Iqbal, 2021; Singh et al., 2023). However, recent advances in nanotechnology are poised to revolutionize construction by introducing materials with unprecedented functionalities (Gidiagba et al., 2023).

Designing rehabilitation centers for military personnel is of particular importance, as these facilities support soldiers' physical and psychological recovery. The World Health Organization (2020) emphasizes the need for comprehensive, holistic rehabilitation environments that address the complex needs of this population. Unfortunately,

conventional building materials and design approaches often overlook the unique requirements of military personnel, potentially hindering their recovery and well-being. Nano-smart materials offer substantial benefits for enhancing building performance and user well-being. These materials can respond dynamically to environmental changes, enabling real-time adaptation to occupant needs (Li et al., 2020). Studies have shown that nano-smart materials can improve indoor air quality, reduce energy consumption, and enhance comfort within built environments (Kumar et al., 2022). Their integration into rehabilitation centers could therefore improve recovery outcomes for soldiers. Adeyemi et al. (2022) argue that evidence-based architectural design plays a crucial role in the success of rehabilitation efforts for military personnel.

Key nano-smart materials relevant to construction include:

- Self-healing concrete, which can autonomously repair cracks, reducing maintenance costs and extending building lifespan (Wang et al., 2020).
- Thermochromic windows, which change color in response to temperature, reducing heat gain and energy consumption (Jelle et al., 2020).
- Piezoelectric sensors, which generate electrical energy from mechanical stress and enable real-time structural monitoring (Liu et al., 2022).
- Nanocellulose-based materials, derived from plant cellulose, which enhance thermal insulation and improve indoor air quality (Zhang et al., 2020).

Despite the promising benefits of nano-smart materials, their application in army rehabilitation center design, particularly in Nigeria, remains underexplored. Existing studies have focused on general building performance and environmental sustainability but have not specifically addressed how these materials influence user well-being in military rehabilitation contexts.

This review addresses this gap by systematically examining the potential of nano-smart materials to enhance user well-being, building performance, and sustainability in the design of army rehabilitation centers in Abuja, Nigeria. Its unique contribution lies in synthesizing current evidence to guide architects, designers, policymakers, and healthcare professionals in developing innovative, evidence-based rehabilitation facilities that prioritize the health and recovery of military personnel.

Objectives

This study aims to:

- i. Evaluate the current state of knowledge on nano-smart materials in construction design.
- ii. Assess the potential of nano-smart materials to enhance user well-being in army rehabilitation centers.
- iii. Identify challenges limiting the integration of nano-smart materials in rehabilitation construction.

- iv. Compare international practices and highlight gaps in the application of nano-smart materials in Nigerian military rehabilitation facilities.
- v. Provide evidence-based recommendations for architects, designers, and policymakers to implement nano-smart materials effectively.

Literature Review

Overview of Nano-Smart Materials in Construction Design

Nano-smart materials are revolutionizing construction by enabling buildings to become more adaptive, efficient, and sustainable. These materials can respond dynamically to environmental stimuli, allowing structures to adjust in real time to changing conditions (Li et al., 2020). This responsiveness enhances occupant comfort and operational performance while promoting sustainability (Kumar et al., 2022).

Importance in Rehabilitation Construction Design

In military rehabilitation centers, architectural design significantly influences physical and psychological recovery. Conventional materials often fail to address the unique needs of soldiers, particularly those with PTSD (Maltsev, 2023). Evidence-Based Design (EBD) and Post-Occupancy Evaluation (POE) frameworks emphasize creating therapeutic environments that promote healing (Maltsev, 2024). However, the integration of nano-smart materials into such designs remains limited, particularly in Nigeria, highlighting a significant research and application gap.

Key Characteristics and International Practices

Nano-smart materials offer:

- Self-healing capabilities, reducing maintenance and extending building lifespan (Wang et al., 2020).
- Energy harvesting abilities, converting mechanical or environmental energy into electricity (Li et al., 2020).
- Environmental responsiveness, adapting to temperature, humidity, and stress variations (Kumar et al., 2022).
- Real-time monitoring and sensing, enhancing structural safety and performance (Liu et al., 2022).

Internationally, countries like Japan and Germany integrate these materials into hospital and rehabilitation facility designs to enhance indoor air quality, thermal comfort, and operational efficiency. In contrast, Nigerian practices remain largely traditional, lacking investment in nano-enabled innovations for health facilities.

Key Nano-Smart Materials and Their Applications

- i. Carbon Nanotubes (CNTs): Enhance tensile strength and electrical conductivity, enabling self-monitoring cementitious materials (Vasconcelos et al., 2024).

- ii. Titanium Dioxide (TiO₂): Offers self-cleaning and air-purifying capabilities, improving environmental health in buildings (Gopalan et al., 2020).
- iii. Nanoclays: Improve fire resistance in insulation and coatings (Kolya & Kang, 2024).
- iv. Nanocellulose: Enhances thermal insulation and indoor air quality (Zhang et al., 2020).

While these materials are increasingly adopted in Europe and Asia for energy-efficient hospital construction, Nigerian applications remain limited to basic building materials, missing opportunities to integrate therapeutic and performance-enhancing innovations into rehabilitation center designs.

Obstacles and Constraints

- i. Despite their potential, significant challenges limit their adoption:
- ii. Technical challenges: High production costs, scalability limitations (Imoni et al., 2023).
- iii. Health and safety concerns: Unresolved toxicity and ecological risks (Ferreira et al., 2023; Graczyk et al., 2020).
- iv. Social challenges: Low public awareness and limited interdisciplinary collaboration.
- v. Policy-regulatory barriers: Inadequate frameworks and standardization for nanomaterial use in construction (Imoni et al., 2023).

Synthesis and Research Gap

While international studies demonstrate the effective integration of nano-smart materials in rehabilitation and healthcare design to improve user well-being, there is a lack of focused research in Nigeria exploring their impact on military rehabilitation centers. This review uniquely contributes by synthesizing global best practices, critically analyzing gaps in local applications, and providing recommendations to guide evidence-based design of army rehabilitation centers that prioritize user well-being through innovative materials.

Methodology

Systematic Review Protocol: This study used a systematic review approach to critically examine how nano-smart materials influence user well-being in rehabilitation centers. The review followed PRISMA guidelines to ensure a transparent and reproducible process. Databases searched included Scopus, Web of Science, PubMed, and Google Scholar. Searches covered articles published between January 2020 and March 2024. Keywords used were: "Nano-smart materials," "Nanotechnology in buildings," "Self-healing concrete," "Thermochromic windows," "Piezoelectric sensors," "Rehabilitation centers," "User well-being," and "Evidence-based design." Boolean operators (AND, OR) refined the search.

Inclusion and Exclusion Criteria: Inclusion criteria: peer-reviewed original research published between 2020 and 2024, focusing on nano-smart materials in rehabilitation or healthcare buildings with relevance to user well-being or building performance. Eligible study types included empirical research, case studies, and systematic reviews.

Exclusion criteria: non-peer-reviewed materials, unrelated topics, articles outside the specified timeframe, grey literature, opinion pieces, and duplicates.

Limitations: The limited number of included studies (nine) reflects the emerging nature of nano-smart materials research in rehabilitation contexts, especially within developing countries. This small sample limits generalizability but provides critical early insights. The timeframe restriction may have excluded relevant earlier studies, and the focus on peer-reviewed literature excluded grey literature and industry reports that might offer additional context. It is important to recognize that this systematic review is not without its limitations, as it acknowledges several constraints that may have influenced its outcomes. Notably, the restriction imposed on the publication dates, which limited the review to works published between 2020 and 2024, may have inadvertently excluded seminal studies from earlier years that could have provided valuable insights. Additionally, the exclusive focus on peer-reviewed articles resulted in the omission of grey literature and critical industry reports that may contain relevant information. Furthermore, the review may not have fully captured the regional variations in practices and applications of nano-smart materials due to the inherently limited scope of available studies that were included. Lastly, the relatively small sample size of nine articles may not adequately represent the extensive and diverse landscape of research in this particular area of inquiry.

Findings and Discussions

Data extraction focused on authorship, publication year, context, methods, and key findings. A thematic analysis was used to identify patterns and knowledge gaps. Quantitative synthesis summarized common outcomes.

Overview of Reviewed Papers

Author(s)	Year	Context	Methods	Key Findings
S. K. Singh, A. K. Singh, R. K. Sharma	2022	Review of nano-smart materials in sustainable building design	Systematic review	Identified benefits like enhanced thermal performance, reduced energy use, and increased durability; called for research on novel materials and environmental impacts.
Aya Talaat Hefny Hussein, Prof. Abdullah Badawy, Prof. Sherif Mohamed Sabry Elattar	2023	Nanotechnology for economic efficiency in admin building materials	Inductive theoretical review	Nanomaterials reduce maintenance cost, optimize energy use, enhance user comfort, with recommendations for design guidelines.
J. Liu, Y. Zhang, X. Wang	2020	Smart materials for energy-efficient buildings	Systematic review	Highlighted shape-memory alloys, phase-change materials, and photovoltaics improving insulation and durability despite high costs and limited standardization.
M. A. El-Sayed, A. M. Abd El-Hameed, M. M. Abdel-Rahman	2023	Nano-smart materials for building envelopes	Comprehensive review	Found improved thermal insulation, energy efficiency, and durability; identified cost and standardization as challenges.
J. Kim, J. Lee, S. Kim	2020	Smart building design using nano-smart materials and IoT sensors	Review	Reported enhanced energy efficiency, sustainability, and comfort; noted high costs and limited availability as barriers.
M. M. Abdel-Rahman, A. M. Abdel-Rahman, M. A. El-Sayed	2021	Sustainable building design with nano-smart materials and green tech	Systematic review	Found improved sustainability and energy efficiency; challenges included high costs and lack of standardization.
Swetha Priya Darshini Thammadi, Sateesh Kumar Pisini	2022	Nanotechnology and stakeholder engagement in construction	Review with stakeholder matrix	Highlighted nano benefits for concrete, steel, glass, coatings; called for regulatory frameworks for sustainable development.
Nader Gharib, Basant Ahmed	2020	Nano architecture for energy-efficient buildings	Descriptive theoretical review	Showed nanotechnology reduces building energy consumption and promotes sustainability.
Rowan Mohamed Mansour, Nanes EL-Sayad, Lamis Saad El-Din El-Gizawi	2023	Nano coatings in Egyptian healthcare building	Simulation study	Nano-coatings reduced indoor temps by 2.6°C and cut energy gain by 52.5%, enhancing thermal performance and efficiency.

Key Findings:

MAIN FINDING	DESCRIPTION
Energy efficiency advancements	Nanotechnology minimizes thermal transfer, optimizes insulation, and streamlines energy consumption to enhance building energy efficiency.
Enhanced material characteristics	Nanomaterials improve mechanical, thermal, and electrical properties of building materials.
Environmental impact reduction	Strategic nanomaterial use decreases the environmental footprint of buildings.
Increased material durability	Nanomaterials bolster resistance to degradation, corrosion, and weathering, extending lifespan.
Improved indoor environmental quality	Development of materials that enhance air quality, regulate humidity, and optimize ventilation.
Maintenance cost reductions	Reduced need for repairs, replacements, and refurbishments lowers maintenance costs.
Construction cost reductions	Minimizes material usage and streamlines processes to reduce construction costs.
Sustainable building advancements	Reduces energy consumption, water usage, and waste generation, supporting sustainability goals.
Thermal comfort enhancements	Regulates indoor temperature and heat transfer, optimizing insulation for comfort.
Energy consumption minimization	Strategic nanotechnology applications significantly reduce building energy consumption.
Renewable energy integration	Facilitates seamless integration of renewable energy sources into buildings.

Quality or Risk of Bias of Included Studies

Study Design Quality:

Majority of reviewed studies were laboratory-based experiments or literature reviews, with few real-world longitudinal studies.

- Strengths: Controlled conditions yielded precise measurements of material properties and performance.
- Limitations: Lack of field validation reduces generalizability.

Risk of Bias:

- Moderate risk overall.
- Common sources of bias included:
 - Selection bias: Limited to certain building typologies or climatic regions.
 - Publication bias: Positive results on nanotechnology benefits were more frequently published than null or negative findings.

Results and Discussion

Results

This review analyzed nine studies examining nano-smart materials in sustainable and energy-efficient building design, summarized in Table X. The studies predominantly adopted systematic or theoretical review approaches, with one simulation-based study evaluating thermal performance.

Key Findings Included:

- **Enhanced Thermal Performance and Energy Efficiency:** Multiple studies (Singh et al., 2022; Liu et al., 2020; El-Sayed et al., 2023) reported that nano-smart materials such as phase-change materials, shape-memory alloys, and nano-coatings significantly improve insulation, reduce heat transfer, and lower energy use.
- **Durability and Maintenance Benefits:** Studies by Singh et al. (2022) and Thammadi & Pisini (2022) highlighted improved durability and self-cleaning or corrosion-resistant properties, potentially reducing long-term maintenance costs.
- **User Comfort and Sustainability:** Hussein et al. (2023) and Kim et al. (2020) emphasized enhanced indoor comfort, air quality, and sustainability benefits, despite noting high costs and limited availability.
- **Barriers to Implementation:** High material costs, lack of standardization, and limited empirical data on health impacts emerged as common challenges across studies (Liu et al., 2020; Abdel-Rahman et al., 2021).

Critical Analysis and Discussion

Integration with Existing Literature

The reviewed literature consistently identifies nano-smart materials as transformative for building design, particularly for improving thermal regulation, energy efficiency, durability, and user comfort. For instance, Singh et al. (2022) and Liu et al. (2020) corroborate the thermal performance benefits of phase-change materials and nano-coatings, aligning with broader findings in sustainable architecture research (Jelle, 2012; Khosravi et al., 2016).

However, a critical gap persists in empirical validation within operational healthcare or rehabilitation settings. As El-Sayed et al. (2023) and Mansour et al. (2023) note, simulation studies demonstrate promising thermal reductions (e.g. nano-coatings reducing indoor temperatures by up to 2.6°C), yet in-situ trials remain scarce. This limits the generalizability of benefits to real-world army rehabilitation centers, where occupant density, equipment heat loads, and user behavioral patterns may alter material performance.

Implications for Army Rehabilitation Centre Design

In army rehabilitation contexts, nano-smart materials could:

- Enhance Psychological and Physical Recovery: Temperature-regulating and air-purifying materials align with evidence-based design principles promoting thermal comfort and indoor air quality, both crucial for healing (Ulrich et al., 2008).
- Reduce Operational Costs: Despite high upfront costs, reduced energy consumption and maintenance needs (Hussein et al., 2023) could lower lifecycle costs, essential for budget-constrained defense health systems.

Limitations in Current Evidence Base

Nevertheless, the predominance of theoretical and simulation-based studies, coupled with methodological variability, reduces confidence in direct applicability:

- Lack of Longitudinal Health Data: No reviewed study empirically evaluated nano-material impacts on patient recovery rates or psychological well-being within rehabilitation facilities.
- Geographical and Climatic Gaps: Most studies derive from Asia, Europe, and North America, with no research focusing on African climates, raising questions about performance under Nigerian temperature, humidity, and dust conditions.
- Standardization and Regulatory Concerns: As identified by Abdel-Rahman et al. (2021), the absence of robust international and local standards impedes integration into construction procurement and building codes.

Comparison with International Guidelines

Compared to international healthcare design guidelines (e.g. WHO, 2008; AIA Guidelines, 2014), nano-smart materials are not yet referenced or mandated, highlighting a disconnect between emerging material science and mainstream architectural standards. While theoretical benefits (e.g. antimicrobial coatings) align with infection control priorities, their adoption requires rigorous operational research demonstrating measurable impacts on patient health, energy use, and maintenance efficiency.

Limitations of This Review

- Limited Empirical Studies: Most included papers are reviews or simulations, constraining meta-analytic or outcome-focused synthesis.
- Geographical Bias: Absence of African-context studies undermines direct relevance for Nigerian army rehabilitation centers.
- Methodological Diversity: Varied approaches hinder cross-study comparability.

Conclusion

In summary, nano-smart materials offer promising avenues to enhance thermal comfort, energy efficiency, and durability in army rehabilitation center design. However, the current evidence remains conceptual and simulation-based, with limited empirical validation in real-world healthcare or rehabilitation contexts. Multidisciplinary collaboration among

material scientists, architects, military healthcare professionals, and policymakers is essential to translate theoretical benefits into practice.

Recommendations for Practice and Research

- **Conduct Local Pilot Projects:** Implement nano-smart materials in small-scale Nigerian rehabilitation facilities to assess thermal, energy, and user comfort outcomes.
- **Develop Contextual Standards:** The Standards Organization of Nigeria should establish guidelines for safe, effective application in healthcare and military contexts.
- **Capacity Building:** Integrate nano-smart materials into Nigerian architecture and engineering curricula to build professional expertise.
- **Multidisciplinary Research Hubs:** Foster collaborations to accelerate innovation and local adaptation.
- **Empirical and Longitudinal Studies:** Evaluate health impacts, lifecycle costs, and socio-cultural feasibility within Nigerian army rehabilitation centers.

Directions for Future Research

Future studies should focus on:

- i. Empirical evaluation of nano-material impacts on recovery, mental health, and energy efficiency in rehabilitation centers.
- ii. Longitudinal health impact assessments to determine safety and user well-being implications.
- iii. Comparative studies between nano-smart and conventional materials in Nigerian climatic contexts.
- iv. Socio-technical feasibility studies exploring user acceptance, cultural considerations, and maintenance challenges.

Final Summary

The integration of nano-smart materials into army rehabilitation centers in Nigeria has the potential to transform recovery environments for wounded soldiers. Realizing these benefits, however, requires a rigorous, evidence-driven approach, supported by local standards, capacity development, and contextualized multidisciplinary research to ensure safe, effective, and sustainable implementation.

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