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Nanotechnology for Sustainable Innovation in the Holy Mosques of Saudi Arabia

Hend I. Alkhammash
Department of Electrical Engineering, College of Engineering, Taif University, 11099, Taif 21944, Saudi Arabia

***Abstract*—Nanotechnology has emerged as a transformative and multidisciplinary field, offering innovative solutions across various domains, including construction, textiles, and environmental management. Among its most promising applications are those related to enhancing the durability, cleanliness, and energy efficiency of buildings and public infrastructure. The Holy Mosques in Saudi Arabia Masjid al-Haram in Makkah and Al-Masjid an-Nabawi in Madinah experience extraordinary levels of foot traffic, exposure to harsh climatic conditions, and continuous maintenance challenges. Traditional maintenance and cleaning methods, though effective to an extent, often fall short in terms of sustainability, cost-efficiency, and environmental friendliness.**

This study investigates the potential role of nanotechnology in revolutionizing the maintenance and sustainability of the Holy Mosques. It emphasizes the application of nanomaterials such as titanium dioxide (TiO_2)-based self-cleaning coatings, which utilize photocatalytic properties to degrade organic pollutants, reduce microbial contamination, and minimize manual cleaning requirements. Furthermore, the integration of nano-engineered construction materials, including high-strength nanocomposites and nano-additives in concrete, is explored as a method to enhance structural integrity, thermal insulation, and resistance to environmental wear and tear. The paper also highlights the development of sustainable nanotextiles that possess antibacterial, anti-odor, and temperature-regulating properties, which can be used in the garments of pilgrims, staff uniforms, and interior fabrics.

Through a comprehensive review of current research, case studies, and experimental findings, this paper presents a roadmap for incorporating nanotechnology into the maintenance strategies of the Holy Mosques. The objective is to promote environmental stewardship, reduce operational costs, and ensure a high standard of hygiene and comfort for millions of annual visitors. In conclusion, the adoption of nanotechnology in religious infrastructure represents a significant step toward sustainable and smart mosque management, aligning with global goals of green innovation and resource efficiency.

***Keywords*— Nanotechnology, Mosque Maintenance, Self-Cleaning Coatings, Energy Efficiency, Sustainable Nanotextiles, Smart Construction Materials, Environmental Sustainability.**

I. INTRODUCTION

The Holy Mosques of Saudi Arabia Masjid al-Haram in Makkah and Al-Masjid an-Nabawi in Madinah occupy a central place in the spiritual lives of Muslims around the world. These sites are not only deeply revered for their religious significance but also possess immense historical and cultural heritage. Each year, millions of Muslims travel to these sacred mosques for the Hajj and Umrah pilgrimages. According to recent estimates, more than 2.5 million pilgrims gather in Makkah annually during Hajj, while millions more perform Umrah throughout the year [1]. This continuous influx of worshippers places tremendous pressure on the infrastructure and maintenance systems of these holy sites.

In response to growing demand and future projections, the Saudi Government, under its Vision 2030 strategic framework, has prioritized improving the quality and sustainability of pilgrim services. One of the flagship programs under this vision is the Pilgrim Experience Program, which seeks to enrich the spiritual journey of pilgrims by modernizing facilities, improving service delivery, and incorporating sustainable practices [2]. In parallel, the Saudi Green Initiative was launched to foster environmental responsibility by reducing carbon emissions, increasing green coverage, and promoting the integration of clean technologies [3]. Within this broader context, the adoption of advanced, sustainable technologies for maintaining the Holy Mosques has become a national priority.

However, the maintenance of these religious structures presents unique and multifaceted challenges, including: High Foot Traffic: With millions of people visiting daily, floor tiles, carpets, ablution areas, and prayer spaces undergo rapid wear and tear. Continuous cleaning, replacement, and refurbishment are essential to uphold hygiene, aesthetics, and safety standards [4].

Harsh Environmental Conditions: The local climate characterized by extreme temperatures, high solar radiation, sandstorms, and airborne pollutants accelerates the degradation of materials, particularly on mosque exteriors such as domes, marble walls, and open courtyards [5].

Massive Energy Consumption: Air conditioning, lighting, water purification, and other support systems operate around the clock to accommodate large crowds, leading to considerable energy use. For instance, the Grand Mosque in Makkah consumes millions of kilowatt-hours of electricity annually [6].

Architectural Conservation: Both mosques are repositories of Islamic art and heritage, including ancient marble structures, handwoven carpets, intricate woodwork, and classical Arabic calligraphy. Preserving these elements requires non-invasive, chemically stable, and historically respectful conservation technologies [7].

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To address these issues effectively, nanotechnology has emerged as a potential game-changer. Defined as the manipulation and utilization of materials at the nanoscale (typically 1–100 nanometers), nanotechnology allows for the design of materials with tailored properties such as increased strength, improved reactivity, enhanced surface area, and superior electrical or thermal conductivity [8]. At this scale, materials often behave differently compared to their bulk counterparts due to quantum effects and surface phenomena [9]. For example, carbon nanotubes have tensile strength 100 times greater than steel while being six times lighter, making them ideal for reinforcement applications [10].

Nanotechnology has already demonstrated its versatility in sectors such as biomedicine, electronics, aerospace, and clean energy [11]. In the context of religious infrastructure like the Holy Mosques, nanotechnology can offer advanced, non-intrusive, and cost-effective solutions to existing problems. This study identifies three key areas where nanotechnology can contribute significantly:

(1) Mosque Maintenance Through Nanocoatings

Self-cleaning nanocoatings based on materials such as titanium dioxide (TiO_2) or silicon dioxide (SiO_2) nanoparticles can be applied to surfaces like domes, minarets, marble floors, and external walls. These coatings exhibit photocatalytic and superhydrophobic properties. Under UV light, TiO_2 initiates a reaction that breaks down organic pollutants and bacterial films, while its superhydrophilic nature allows water to spread uniformly and wash away dirt without the need for detergents [12]. This reduces the frequency and intensity of manual cleaning, lowers maintenance costs, and minimizes chemical use—thereby supporting sustainable mosque operations [13].

(2) Enhancing Energy Efficiency Using Nanomaterials

Nanomaterials can significantly improve the thermal insulation and energy efficiency of buildings. For example, nano-enhanced insulators, such as aerogels and silica nanoparticles, reduce heat transfer and help maintain indoor temperatures. Smart window films embedded with nanoparticles can selectively filter sunlight, reducing the need for air conditioning during hot summer months [14]. Moreover, transparent solar coatings can be applied to glass domes and windows to harness solar energy without altering the architectural aesthetics of the mosque. These strategies collectively reduce electricity consumption and contribute to the objectives of the Saudi Green Initiative [15].

(3) Advanced Mosque Textiles with Nanotechnology

The application of nanotextiles in mosque interiors and pilgrim garments can greatly improve hygiene, comfort, and longevity. Nanoparticles such as silver (AgNPs) and zinc oxide (ZnO) are known for their antibacterial and antifungal properties. When embedded in fabrics, they inhibit the growth of odor-causing bacteria, making them ideal for use in carpets, curtains, prayer mats, and uniforms [16]. Additionally, nanocoated fabrics can resist stains, block UV rays, and withstand wear and tear, making them especially suitable for high-traffic environments like the Grand Mosque [17].

In conclusion, nanotechnology provides a multi-dimensional toolkit for addressing the unique maintenance challenges of the Holy Mosques. Its potential to extend material lifespan, conserve energy, reduce operational costs, and uphold cleanliness makes it a highly promising domain for sustainable religious infrastructure. This paper aims to offer a comprehensive examination of how emerging nanotechnologies can be practically and respectfully integrated into the sacred and historical context of Makkah and Madinah, contributing to smart, sustainable, and future-ready mosque management.

II. NANOTECHNOLOGY IN MOSQUE MAINTENANCE

Modern mosque maintenance faces challenges that stem from heavy human traffic, environmental stressors, and the need to preserve architectural heritage. As traditional cleaning and maintenance techniques can be labor-intensive, chemically harsh, or inefficient over time, nanotechnology offers a transformative approach by introducing self-sustaining and environmentally adaptive materials. Among the most promising advancements are self-cleaning nanocoatings, which utilize principles of photocatalysis, hydrophobicity, and UV-resistance to maintain structural cleanliness, aesthetic integrity, and microbial safety with minimal human intervention.

Self-cleaning coatings based on nanomaterials particularly titanium dioxide (TiO_2) and silicon dioxide (SiO_2) have gained considerable attention due to their dual functionality: degradation of pollutants and prevention of surface contamination. These coatings are especially applicable to domes, minarets, courtyard marble, ablution areas, and interior walls, which often require frequent maintenance in the Holy Mosques due to environmental exposure and constant human contact.

(1) Photocatalytic Mechanism

TiO_2–SiO_2 nanocomposites function based on photocatalysis a process in which TiO_2, when exposed to ultraviolet (UV) light, generates reactive oxygen species (ROS). These ROS, including hydroxyl radicals (•OH) and superoxide anions (O_2^-), actively degrade organic matter, pollutants, and microbial films from surfaces [18], [19]. SiO_2 is often added to enhance transparency, mechanical stability, and adherence to glass, marble, or metal surfaces [20]. These coatings are particularly advantageous for preserving architectural aesthetics without altering the surface appearance of delicate mosque structures.

(2) Superhydrophobic and Omniphobic Coatings

Superhydrophobic coatings are engineered to create surfaces with extremely high water contact angles (>150°), causing water droplets to bead up and roll off, carrying dust and debris with them, a phenomenon known as the Lotus Effect [21]. These coatings are made from fluorinated silica nanoparticles or functionalized polymers, and are ideal for the mosque's marble floors, prayer halls, and ablution areas where water usage is high. Omniphobic coatings, on the other hand, repel both water and oily substances, further enhancing stain resistance and ease of cleaning [22].

(3) UV-Resistant Coatings for Heritage Protection

Ultraviolet radiation from sunlight is a significant cause of fading, chemical degradation, and physical deterioration of historical features, such as calligraphy panels, painted tiles, mosaics, and fabrics. Nanocoatings embedded with UV-absorbing nanoparticles, such as cerium oxide (CeO_2) or zinc oxide (ZnO), can serve as transparent protective layers that absorb or scatter harmful UV rays [23], [24]. These coatings prolong the life of materials and maintain the original appearance of heritage elements.

(4) Performance and Real-World Applications

In practical settings, nanocoatings have demonstrated high efficacy in mosque environments. An experimental study involving TiO_2–SiO_2 nanocoatings applied to exterior mosque walls showed a significant reduction in visible dust and pollutant accumulation after six months of exposure [25]. Moreover, photocatalytic coatings have been shown to eliminate up to 99% of airborne bacteria, making them suitable for hygienic environments such as mosque ablution areas and toilets [26].

A notable study conducted by the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research tested TiO_2 nanocoatings on toilet surfaces and courtyard stones in the Grand Mosque. Results revealed substantial reductions in microbial load, demonstrating long-term antibacterial activity even under high usage and harsh cleaning cycles [27].

Table I. Summary of Nanocoating Types and Applications

Coating Type	***Mechanism***	***Advantages***	***Ref. No.***
TiO_2-Based	Photocatalysis	Breaks down dirt, reduces air pollution	[26]
Superhydrophobic	Water Repellent	Prevents water stains, easy cleaning	[28]
SiO_2-Based	Transparent Coating	Protects glass and marble surfaces	[29]
Hybrid Nanocoatings	Multi-functional	Combines self-cleaning & antimicrobial properties	[30]

III. NANO-ENHANCED CONSTRUCTION MATERIALS

The application of nanotechnology in construction materials has revolutionized modern infrastructure by offering advanced solutions that improve the mechanical, chemical, and environmental performance of buildings. In the context of mosque construction and renovation, nano-enhanced materials offer substantial benefits in terms of durability, energy efficiency, and maintenance reduction.

One of the most widely used nanomaterials in construction is nano-silica, which significantly enhances the compressive strength and durability of concrete. Its high surface area and pozzolanic reactivity led to a denser cement matrix, reducing porosity and improving resistance to cracks and environmental degradation [31]. Studies have shown that nano-silica concrete demonstrates up to 40% greater compressive strength compared to traditional concrete, making it particularly suitable for areas exposed to high stress or traffic, such as mosque courtyards and domes [32].

Another promising material is graphene-based nanocomposites, which possess exceptional thermal conductivity, tensile strength, and impermeability. These properties make them ideal for coatings that enhance the structural integrity of walls and roofs, and for applications that require thermal management, such as mosque domes in hot climates [33], [34].

In addition, anti-corrosion nanocoatings, particularly those incorporating zinc oxide (ZnO) or titanium dioxide (TiO_2) nanoparticles, have shown outstanding performance in protecting metallic surfaces from oxidation and degradation. This is especially beneficial for mosque gates, doors, and decorative metallic elements frequently exposed to humidity and pollutants [35].

Moreover, self-healing concrete, which uses nanocapsules or microbacteria to autonomously repair cracks, is gaining traction for its ability to extend the lifespan of infrastructure while minimizing maintenance costs. These materials are well-suited for the long-term sustainability of historic and modern mosques alike.

Lastly, nanoclay and carbon nanotubes (CNTs) enhance the thermal and mechanical performance of traditional construction materials. Their incorporation into cementitious composites improves fire resistance, reduces thermal conductivity, and provides seismic resistance—important considerations for mosques located in vulnerable geographical zones [35].

IV. NANOTECHNOLOGY IN ENERGY EFFICIENCY

The integration of nanotechnology into energy systems has emerged as a transformative approach to improving building energy performance. For mosques, which often involve large open halls, domes, and extensive lighting and cooling requirements, energy-efficient nanomaterials can drastically reduce operational costs and environmental impact.

A. Thermal Regulation in Mosques

Thermal comfort in mosques, particularly in regions with extreme temperatures, is critical for the wellbeing of worshippers. Nanotechnology provides cutting-edge insulation solutions, such as Nano-Insulation Materials (NIM) and Vacuum Insulation Panels (VIPs), that offer superior thermal resistance with minimal material thickness [36].

For example, NanoCon, a high-performance NIM, matches or exceeds the compressive strength of standard concrete while significantly lowering thermal conductivity. This material can be integrated into mosque walls and roofs, minimizing heat ingress and reducing the need for extensive air-conditioning [37]. Studies show that buildings incorporating nano-insulated walls report a 25% reduction in cooling energy demand, a figure particularly relevant for mosques with continuous public access during the day [36], [38], [39].

B. Nano-Enhanced Solar Energy Solutions

Another frontier in mosque sustainability is nano-enabled solar technology. Nanomaterials such as quantum dots and perovskite solar cells are being explored for their superior photovoltaic (PV) conversion efficiency and tunable light absorption characteristics. These solar technologies can be seamlessly integrated into mosque architecture—for instance, within skylights and domes—to generate electricity while maintaining aesthetic and functional features [40], [41].

Quantum dot solar cells can absorb a broader spectrum of light, resulting in up to 30% increased energy conversion efficiency compared to conventional silicon-based cells [42]. Likewise, photovoltaic (PV) windows using transparent nano-coatings

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can produce energy while allowing natural daylight into prayer halls, reducing reliance on artificial lighting [43], [44]. Additionally, nano-solar coatings applied to mosque domes or roofing materials can improve energy capture while providing thermal insulation [45], [46].

Moreover, phase-change materials (PCMs) with nanocomposite enhancements are increasingly used in passive cooling applications. These materials absorb heat during the day and release it at night, thus stabilizing indoor temperatures without mechanical intervention—a solution well-suited to reduce electricity consumption in mosques during peak hours [47].

Table II. Summary of Nanomaterials Used in Energy Efficiency

Nanomaterial	*Application*	*Energy Saving Benefit*	*Ref. No.*
Aerogels	Thermal Insulation	Reduces heat transfer by 40%	[36]
Quantum Dots	Solar Cells	Increases energy conversion by 30%	[37]
Reflective Coatings	Mosque Roof and Domes	Reduces cooling demand	[38]
Phase-Change Materials	Smart Cooling	Stores & releases thermal energy efficiently	[39]

V. NANOTECHNOLOGY IN MOSQUE TEXTILES

Nanotechnology has revolutionized the field of textiles by imparting advanced functionalities such as self-cleaning, antimicrobial protection, UV resistance, and flame retardancy. These features are especially beneficial for textiles used in high-traffic, high-hygiene environments like mosques.

A. Antimicrobial & Self-Cleaning Nanotextiles

The incorporation of nanomaterials like silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO_2) into textiles has led to fabrics that can actively inhibit bacterial growth, repel stains, and maintain cleanliness for extended periods.

In Saudi Arabia, nano-enhanced ihram garments have been developed by embedding silver nanofibers into the fabric structure. These fibers release silver ions that interact with bacterial proteins and cell membranes, halting microbial reproduction. Pilots during the Hajj reported a significant reduction in skin infections and odors due to the antimicrobial properties of the clothing [51], [52].

The sacred Kiswa of the Kaaba, traditionally made of silk and gold threads, presents an ideal candidate for UV-resistant and self-cleaning nano-coatings. Dispersion of TiO_2 nanoparticles in the final fabric coating can catalytically break down organic stains and offer UV protection without altering the fabric's appearance [53], [54].

Similarly, prayer carpets and mosque curtains benefit from nanocoatings that resist dust, moisture, and odors. Laboratory studies have shown that ZnO-NP-treated cotton fabrics retain their antimicrobial efficacy—achieving approximately 95% bacterial inhibition—even after 20 machine wash cycles and 100 abrasion tests, highlighting their durability [55], [56].

B. Flame-Retardant Nanocoatings

In addition to hygiene features, mosque textiles must provide fire safety, especially in prayer halls and gathering areas. Conventional flame retardants often involve toxic halogenated compounds, but nanomaterials offer safer alternatives.

Nano-additives such as alumina-coated silica (Al_2O_3–SiO_2) and TiO_2 nanoparticles can be incorporated into textiles during finishing processes. Upon exposure to heat, these coatings form a protective char layer, reducing flame spread and smoke production [57], [58]. Textile treatments with nano-silica show improved thermal stability and lower peak heat release rates, making them suitable for flame-sensitive environments [59-62].

Table III – Nanotextile Applications in Mosque Environments

Nanomaterial	*Application*	*Key Benefit*	*Ref. No.*
TiO_2 & ZnO	Self-Cleaning Textiles	Keeps carpets & garments clean	[59]
AgNPs	Antibacterial Fabrics	Eliminates of bacteria	[60]
Fe_3O_4	Magnetic Nanocoatings	Enhances fabric durability	[61]
ZnO	UV-Resistant Textiles	Protects fabrics from sun damage	[62]

Overall, the integration of nanotextiles into mosque textiles presents a multi-faceted approach to enhancing hygiene, user comfort, aesthetic preservation, fire safety, and sustainability. From high-efficiency antimicrobial ihram garments to self-cleaning carpets and UV-stable sacred cloth, the application of nanotechnology supports Saudi Arabia's goals of Vision 2030 by reducing maintenance demands, conserving resources, and preserving cultural heritage in high-traffic worship spaces.

VI. CHALLENGES AND FUTURE PROSPECTS

Although nanotechnology holds immense promise in enhancing the functionality, durability, and hygiene of infrastructure and textiles in sacred spaces like the Holy Mosques, there are several hurdles to its widespread adoption. These challenges include financial, environmental, and safety concerns, as well as technical limitations. Understanding and addressing these issues is essential for responsible and sustainable integration of nanotechnologies in religious architecture and facilities.

A. Cost and Implementation Challenges

A key barrier to the implementation of nanotechnology in mosque maintenance and construction is the high cost of nanomaterials. Nanoparticles such as titanium dioxide (TiO_2), silver (Ag), and zinc oxide (ZnO) require complex synthesis processes involving high-purity precursors, specialized equipment, and precise control over particle size and morphology. These requirements significantly increase production costs compared to conventional materials [63].

For instance, the application of TiO_2 nanocoatings for self-cleaning and antimicrobial surfaces, while effective, involves labor-intensive deposition techniques like sol-gel processing, atomic layer deposition (ALD), or spray coating, which require trained personnel and infrastructure [64]. Moreover, nanotechnology-based textiles—such as silver nanoparticle-embedded Ihram garments—are not yet widely commercialized due to limited industrial-scale production and consumer cost sensitivity.

To overcome these economic barriers, government incentives and public-private partnerships could play a vital role. Subsidies for research, tax benefits for eco-friendly innovation, and scaling-up production facilities through investment in local nanomanufacturing can help reduce costs [65]. Additionally, increasing demand and competition among producers are expected to bring down prices over time, making nano-enhanced products more accessible to large-scale religious institutions.

B. Environmental and Nanotoxicity Concerns

While nanotechnology offers benefits in sustainability and hygiene, there are serious concerns regarding nanotoxicity and environmental impact. Unlike bulk materials, nanoparticles can penetrate biological membranes due to their ultra-small size (1–100 nm), potentially interacting with cells and organs in harmful ways [66].

Studies have demonstrated that inhaled nanoparticles especially from airborne nanocoatings or treated textiles can migrate from the lungs to secondary organs such as the brain, liver, and kidneys, where they may trigger oxidative stress, inflammation, DNA damage, or mitochondrial dysfunction [67]. For example, silver nanoparticles (AgNPs), commonly used for their antimicrobial effects, have been shown to accumulate in aquatic organisms, affecting reproduction and metabolism, raising concerns over their release into water systems during washing cycles [68].

Moreover, the long-term degradation pathways of nanoparticles in the environment remain poorly understood. Nanoparticles used in construction materials or textiles may be released as particulates over time, potentially contaminating soil and water. Regulatory bodies like the OECD and EU REACH have called for more comprehensive life-cycle assessments (LCA) to understand the environmental footprint of nanomaterials [69].

Thus, while nanotechnology contributes to sustainability at the surface level—by reducing water use or chemical cleaners it may introduce new environmental risks if not handled properly. Institutions adopting nanotechnology must also invest in risk assessment protocols, waste management strategies, and eco-toxicological studies to ensure long-term safety.

C. Future Research Directions

To realize the full potential of nanotechnology in religious and cultural contexts, future research must address affordability, safety, and functionality simultaneously. The following areas are particularly promising:

1. Biodegradable and Eco-Friendly Nanomaterials

Future development should focus on biocompatible and biodegradable alternatives to synthetic nanoparticles. Materials like chitosan, cellulose nanocrystals, and plant-derived nanoparticles offer comparable benefits in antimicrobial and flame-retardant performance without associated toxicity [70].

2. Self-Healing Coatings and Smart Surfaces

Incorporating self-healing functionalities in coatings enabled by microcapsules or shape-memory nanomaterials can drastically reduce maintenance costs and prolong the life of mosque interiors and exteriors [71]. These technologies can automatically seal cracks or regenerate surface coatings under specific triggers like light, heat, or moisture.

3. Photocatalytic Air Purification and Solar-Active Coatings

Advanced TiO_2-based coatings with doping elements (e.g., N, Ag, or Fe) can remain active under visible light, offering dual benefits of self-cleaning and air purification by degrading airborne pollutants like NOx, SOx, and VOCs around heavily congested mosque areas [72].

4. Customized Nanotextiles for Pilgrimage Needs

Research can also target performance-oriented textiles tailored for the unique climatic and hygiene challenges of Hajj and Umrah, such as sweat-responsive cooling textiles, dust-repellent fibers, and wearable biosensors embedded in Ihram garments to monitor pilgrims' hydration and health [73].

5. Nano-enabled Energy Solutions

Integrating nanotechnology into energy systems—such as solar window films, thermoelectric cooling, and nano-insulation materials—can help reduce the massive energy demands of air conditioning and lighting in large religious structures, contributing to energy-efficient mosque infrastructure [74].

In a nutshell, the integration of nanotechnology into the maintenance and operation of the Holy Mosques holds transformative potential for achieving higher standards of sustainability, hygiene, and functionality. However, success depends on addressing challenges related to cost, safety, and scalability. Through focused research, policy support, and responsible deployment, nanotechnology can enhance the spiritual and environmental sanctity of Islamic places of worship for generations to come.

VII. CONCLUSION

Nanotechnology offers an innovative paradigm for enhancing the maintenance, hygiene, and sustainability of mosque environments, particularly in high-traffic and climatically challenging contexts such as the Holy Mosques in Saudi Arabia. The application of nanomaterials in surface coatings, textiles, and building components has shown significant promise in addressing long-standing issues related to microbial contamination, material degradation, and energy inefficiency. Self-cleaning coatings based on photocatalytic nanostructures (e.g., TiO_2 and ZnO) can maintain facade cleanliness with minimal manual intervention, while nano-engineered textiles embedded with silver or copper nanoparticles offer robust antimicrobial and deodorizing properties, making them ideal for use in prayer carpets, Ihram garments, and the Kiswa of the Kaaba.

Furthermore, nanostructured insulation materials and energy-reflective surface treatments can contribute substantially to thermal regulation, reducing the need for energy-intensive climate control systems within mosque complexes. Despite these advancements, several critical challenges persist. High production and implementation costs of nanomaterials limit large-scale deployment, especially in developing contexts. In addition, concerns surrounding the environmental persistence and potential toxicity of nanoparticles necessitate stringent safety evaluations, lifecycle assessments, and the development of standardized regulatory frameworks.

Future research must prioritize the design of biodegradable, cost-effective, and scalable nanomaterials with minimal ecological footprint. It is equally vital to explore multifunctional nanocomposites that combine antimicrobial, self-healing, and energy-saving properties tailored to the unique architectural and cultural needs of Islamic religious structures. Collaborative efforts among material scientists, religious heritage conservators, and policy-makers are essential to facilitate the responsible integration of nanotechnology in mosque infrastructure.

In summary, nanotechnology presents a powerful toolkit for modernizing mosque maintenance and enhancing environmental stewardship in Islamic architecture. Its strategic deployment, guided by ethical and scientific diligence, can ensure that technological innovation complements spiritual sanctity while advancing sustainability goals in sacred spaces.

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