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BIO-BASED NANOMATERIALS FOR ANTIMICROBIAL BUILDING SURFACES: PERFORMANCE, DURABILITY AND SAFETY ASSESSMENT

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ABSTRACT
The increasing demand for antimicrobial building surfaces, particularly in healthcare facilities, educational institutions, and public spaces, has driven significant research into bio-based nanomaterials as sustainable alternatives to conventional synthetic antimicrobial agents. This comprehensive review examines the current state of bio-based nanomaterials for antimicrobial building surface applications, focusing on performance characteristics, durability assessments, and safety considerations. We analyze various categories of bio-based nanomaterials including chitosan nanoparticles, cellulose nanocrystals, lignin-derived nanocomposites, and essential oil-loaded nanosystems. The review synthesizes recent advances in fabrication techniques, antimicrobial mechanisms, and integration strategies for building materials. Key performance metrics, including antimicrobial efficacy, mechanical properties, and environmental stability are critically evaluated. Durability challenges such as UV degradation, moisture sensitivity, and mechanical wear are discussed alongside emerging solutions. Safety assessment protocols and regulatory considerations for bio-based nanomaterials in built environments are examined. The review concludes with identification of research gaps and future directions for developing commercially viable bio-based antimicrobial building surfaces that balance performance, sustainability, and human safety.

KEYWORDS: bio-based nanomaterials, antimicrobial surfaces, building materials, sustainability, nanotechnology, safety assessment.

1. INTRODUCTION
The global antimicrobial building materials market has experienced unprecedented growth, driven by heightened awareness of infection control following the COVID-19 pandemic and increasing antibiotic resistance concerns (Abutu *et al.*, 2025). Traditional antimicrobial building surfaces often rely on synthetic compounds such as quaternary ammonium compounds, silver-based agents, and copper alloys, which raise environmental and health concerns regarding toxicity, bioaccumulation, and contribution to antimicrobial resistance (Motamedi *et al.*, 2025). Consequently, there is growing interest in bio-based nanomaterials as sustainable alternatives that can provide effective antimicrobial properties while minimizing environmental impact. Bio-based nanomaterials derived from natural sources such as plant biomass, microbial fermentation products, and marine organisms offer unique advantages including biodegradability, biocompatibility, and renewable sourcing (Ikeh, 2024; Motamedi *et al.*, 2025). These materials can be engineered at the nanoscale to enhance their antimicrobial properties through increased surface area, controlled release mechanisms, and synergistic effects with other natural compounds (Agnihotri and Dhiman, 2017; Ike, 2024). However, the translation of bio-based nanomaterials from laboratory research to commercial building applications requires comprehensive evaluation of their performance, durability, and safety characteristics under real-world conditions.

Nanomaterials and cationic polymers have shown unprecedented advantages as effective antimicrobial therapies due to their flexibility and ability to interact with biological macromolecules (Agnihotri and dhiman, 2017). They can incorporate a variety of antimicrobial substances, achieving multifunctional effects without compromising the structural integrity of building materials. The use of metal and metal oxide nanoparticles, such as silver, titanium dioxide, or zinc oxide, as additives to bulk materials or coatings and paints improves the resistance of building materials to biological factors by providing antimicrobial functions (Motamedi *et al*., 2025).

This review provides a critical analysis of current research on bio-based nanomaterials for antimicrobial building surfaces, examining the fundamental principles governing their antimicrobial activity, fabrication techniques, integration strategies, and performance optimization approaches. We address key challenges including durability limitations, scalability issues, and regulatory considerations that influence commercial adoption. The review aims to provide researchers, materials scientists, and industry professionals with a comprehensive understanding of the current state and future prospects of bio-based antimicrobial building materials.

2. Classification and Sources of Bio-based Nanomaterials

2.1 Polysaccharide-based Nanomaterials

Polysaccharide-derived nanomaterials represent the largest category of bio-based antimicrobial agents for building applications. Chitosan, derived from chitin deacetylation, has emerged as a leading candidate due to its intrinsic antimicrobial properties and excellent film-forming capabilities (Munteanu *et al*., 2021; Souza *et al*., 2023) For many years, chitosan has been widely regarded as a promising eco-friendly polymer thanks to its renewability, biocompatibility, biodegradability, and non-toxicity (Souza *et al*., 2023).

Chitosan nanoparticles exhibit broad-spectrum antimicrobial activity through electrostatic interactions with negatively charged bacterial cell membranes, leading to membrane disruption and cell death (Alalawi and Allani, 2025). The synthesis can be conducted by simply stirring a chitosan solution with different amounts of antimicrobial agents at room temperature, and the composite can be applied as a coating on various surfaces (Muhammad *et al*., 2025). In-situ reduction processes during coating application lead to enhanced antimicrobial efficacy and improved adhesion to building substrates.

Cellulose nanocrystals and nanofibrils, extracted from various plant sources including wood, cotton, and agricultural residues, provide mechanical reinforcement and can serve as carriers for antimicrobial agents (Brandelli, 2024). The high aspect ratio and crystalline structure of cellulose nanomaterials contribute to enhanced barrier properties and controlled release of active compounds when incorporated into building surface coatings (Ang *et al*., 2025). Over the past few years, nanocellulose has been proved to be one of the most prominent green materials of modern times due to its unique physicochemical properties and sustainability aspects (El-Hack *et al*., 2020).

2.2 Protein-based Nanomaterials

Protein-derived nanomaterials, including those from silk fibroin, gelatin, and plant proteins, offer unique properties such as pH-responsive behavior and enzymatic degradability (Munteanu *et al*., 2021). Silk fibroin nanoparticles demonstrate excellent biocompatibility and can encapsulate essential oils and natural antimicrobial compounds while providing sustained release over extended periods. The controlled release ensures long-lasting antimicrobial effects, which is particularly important for building surface applications where frequent reapplication may not be practical (Alqahtani *et al*., 2020).

Chitosan-modified microcapsules are receiving close attention as carrier materials or substrates for immobilizing enzymes to maximize catalytic activity and recyclability. Microfluidic production of calcium alginate/chitosan composite microcapsules for enzyme immobilization with ultrathin shells maintained more than 80% of residual activity after six recycle operations (Aranaz *et al*., 2021).

2.3 Lipid-based Nanosystems

Natural lipids and fatty acids can form various nanostructures including liposomes, solid lipid nanoparticles, and nanostructured lipid carriers that serve as delivery systems for hydrophobic antimicrobial compounds (Esmaeili *et al*., 2020). These systems are particularly effective for incorporating essential oils and plant extracts into building surface formulations, addressing challenges related to volatility and oxidation susceptibility.

The development of innovative active systems is a promising strategy to mitigate microbial contamination while enhancing surface performance and extending service life (Orsuwan and Sothomvit, 2018). Pickering emulsions with essential oils are critically evaluated as active additives for sustainable surface coatings, focusing on their antimicrobial and antioxidant properties, stabilization mechanisms, and physicochemical performances.

2.4 Essential Oil-loaded Nanosystems

Essential oils from plants such as tea tree, eucalyptus, thyme, and oregano possess potent antimicrobial properties due to their high content of phenolic compounds, terpenes, and aldehydes (Zhang *et al*., 2019). An effective antibacterial system was developed using clove essential oil Pickering emulsion, where carboxymethyl cellulose sodium modified cellulose nanocrystals were used as the stabilizer (Bilia *et al*., 2014; Motamedi *et al*., 2025). Nanoencapsulation of essential oils addresses challenges related to volatility, oxidation susceptibility, and compatibility with building material matrices. ZnO nanoparticles stabilized oregano essential oil Pickering emulsion can be incorporated into functional cellulose nanofibrils films for antimicrobial and antioxidant activity (Wang *et al.*, 2021). This approach provides controlled release of active compounds while maintaining their bioactivity over extended periods.

3. Antimicrobial Mechanisms and Performance Characteristics

3.1 Mechanism of Action

Bio-based nanomaterials exhibit antimicrobial activity through multiple mechanisms that often work synergistically to enhance efficacy. The primary mechanisms include membrane disruption, reactive oxygen species generation, metal ion chelation, and interference with cellular processes (Sahiner *et al.*, 2022). Understanding these mechanisms is crucial for optimizing material design and predicting performance under different environmental conditions. Chitosan-based nanomaterials primarily function through electrostatic interactions with bacterial cell membranes, causing membrane permeabilization and subsequent cell death (Alalawi and Allani, 2025). The degree of deacetylation and molecular weight significantly influence antimicrobial efficacy, with higher deacetylation degrees generally correlating with enhanced activity. Essential oil-loaded nanosystems release volatile compounds that penetrate microbial cell walls and disrupt cellular functions including respiration, membrane integrity, and enzyme activity (Alalawi and Allani, 2025; Sahiner *et al.*, 2022; Adedoyin and Ogunsona, 2025a, 2025b).

Progress in construction of bio-inspired physico-antimicrobial surfaces has recognized antibacterial effects on surfaces of some natural nanostructures, providing evidence for physical sterilization mechanisms (Abutu *et al.*, 2025). The dragonfly and cicada wings have been found to possess exceptional antibacterial properties because of their specific nanostructures, inspiring biomimetic surface designs for building applications.

3.2 Performance Evaluation Metrics

The performance of bio-based antimicrobial building surfaces is evaluated using standardized test methods adapted for building materials. Key metrics include minimum inhibitory concentration (MIC), minimum bactericidal concentration (MBC), zone of inhibition, and log reduction values against target microorganisms (Munteanu *et al.*, 2021). Long-term efficacy is assessed through accelerated aging tests and real-world exposure studies that simulate building service conditions.

Recent developments in multifunctional antimicrobial surfaces show that implant-associated infections arising from biofilm development have detrimental effects with compromised quality of life for patients (Hasan *et al.*, 2013). It has been a struggle for more than 50 years for the biomaterials field to achieve long-term success by discouraging bacterial and protein adhesion without adversely affecting surrounding tissue and cell functions.

Table 1: Performance Characteristics of Major Bio-based Nanomaterial Categories.

Material Category	Primary Mechanism	Target Microorganisms	Log Reduction*	Duration**	Key Advantages	Limitations	References
Chitosan NPs	Membrane disruption	Bacteria, fungi	3-6	6-12 months	Broad spectrum, biodegradable	pH sensitive, moisture effects	Munteanu *et al.*, 2021; Allalawi and Allani, 2025
Cellulose NC + EO	Controlled release	Bacteria, viruses	2-4	3-8 months	Renewable, mechanical strength	Volatile loss, compatibility	Brandelli, 2024
Lignin composites	ROS generation	Bacteria	2-5	4-10 months	Abundant waste source	Limited spectrum	Abd El-Hack *et al.*, 2020
Essential oil nanosystems	Multi-target	Bacteria, fungi, viruses	4-7	2-6 months	Natural, pleasant odor	Volatility, cost	Wang *et al.*, 2021
Protein NPs	Enzyme inhibition	Bacteria	2-4	6-12 months	Biocompatible	Processing complexity	Ingle *et al.*, 2025

*Log reduction after 24-hour contact time under standard test conditions

**Estimated effective duration under typical indoor conditions

3.3 Factors Influencing Performance

Several factors significantly influence the antimicrobial performance of bio-based nanomaterials in building applications. Particle size and size distribution affect surface area availability and interaction with microorganisms (Agnihotri and Dhiman, 2017). Environmental conditions including temperature, humidity, pH, and UV exposure can alter material stability and release kinetics. The incorporation method and matrix compatibility determine the accessibility and stability of antimicrobial agents within building material formulations. The combination of poly-ε-lysine, chitosan, and natamycin can achieve excellent antimicrobial effects against bacteria and fungi while decreasing the dose of single preservatives (Aranaz *et al*., 2021). High-throughput sequencing revealed that combination antimicrobials provide synergistic effects that enhance overall performance while reducing potential resistance development.

4. Integration Strategies for Building Materials

4.1 Surface Coating Applications

Surface coating represents the most common integration strategy for bio-based antimicrobial nanomaterials in building applications. Coating formulations typically consist of polymer binders, antimicrobial nanoparticles, and functional additives that provide adhesion, durability, and desired surface properties (Ingle *et al*., 2025; Adedoyin and Ogunsona, 2025b). Water-based formulations are preferred for indoor applications due to reduced volatile organic compound emissions and improved occupant safety. The coating application process must ensure uniform distribution of nanomaterials while maintaining their antimicrobial activity. Carboxymethyl chitosan capped bimetallic nanoparticles entrapped in theranostic nanofibers show significant promise for surface applications (Kurul *et al*., 2025). These systems demonstrate antimicrobial peptide coating capabilities with enhanced in vitro and in vivo characterization for multidrug-resistant microbial infections. Quality control measures including coating thickness monitoring and antimicrobial efficacy testing are essential for consistent performance. Novel antimicrobial biodegradable composite films based on shellac/chitosan and $ZnAl_2O_4$ or $CuAl_2O_4$ spinel nanoparticles demonstrate promising properties as surface coating materials (Singh *et al*., 2025; Adedoyin and Ogunsona, 2025c). These composites were created using straightforward and adaptable solution mixing and casting methods.

4.2 Bulk Incorporation Methods

Bulk incorporation involves dispersing bio-based nanomaterials throughout the building material matrix during manufacturing. This approach provides long-lasting antimicrobial properties as active materials are distributed throughout the material volume rather than concentrated at the surface (Brandelli, 2024). However, bulk incorporation requires careful consideration of processing conditions and material compatibility to avoid degradation or aggregation of nanomaterials. Polymer composites, cementitious materials, and ceramic systems have been successfully modified through bulk incorporation of bio-based nanomaterials (Motamedi *et al*., 2025). The incorporation process must be optimized to maintain both antimicrobial efficacy and mechanical properties of the base material. Dispersion quality is critical, as poor distribution can lead to localized weak points and reduced antimicrobial coverage.

4.3 Hybrid Systems and Multilayer Approaches

Advanced integration strategies involve combining multiple bio-based antimicrobial agents or creating multilayer systems with complementary properties (Rashid and Hoque, 2022). Hybrid systems can provide synergistic antimicrobial effects while addressing individual material limitations. For example, combining chitosan nanoparticles with essential oil-loaded nanosystems can enhance both immediate and sustained antimicrobial activity. Metallic nanoparticles have potential to be used in conjunction with chitosan nanoparticles for enhanced antimicrobial applications (Parvin *et al*., 2025). Multilayer approaches involve applying sequential coatings with different functions, such as primer layers for adhesion, active layers containing antimicrobial nanomaterials, and protective topcoats for durability.

5. Durability Assessment and Challenges

5.1 Environmental Degradation Mechanisms

The durability of bio-based antimicrobial building surfaces is challenged by various environmental factors that can degrade the active nanomaterials or compromise their effectiveness. UV radiation exposure represents a primary concern, as many bio-based materials are susceptible to photodegradation that can alter their chemical structure and reduce antimicrobial activity (Abutu *et al*., 2025). Moisture exposure can lead to swelling, dissolution, or hydrolysis of polysaccharide-based materials, while temperature fluctuations can affect material stability and release kinetics. Mechanical wear from cleaning activities, foot traffic, and routine building maintenance poses additional durability challenges. The surface location of many antimicrobial treatments makes them vulnerable to physical removal through abrasion and chemical attack from cleaning agents (AlQurashi *et al*., 2025). Understanding these degradation mechanisms is essential for developing more durable formulations and appropriate maintenance protocols.

5.2 Accelerated Testing Methods

Standardized accelerated testing protocols have been developed to evaluate the long-term durability of antimicrobial building materials under controlled conditions. UV exposure testing using xenon arc or fluorescent UV lamps simulates years of sunlight exposure in condensed timeframes (Abutu *et al*., 2025). Humidity cycling tests evaluate material response to moisture variations, while thermal cycling assesses stability under temperature fluctuations. Abrasion resistance testing using standardized procedures evaluates the mechanical durability of surface treatments. Chemical resistance testing exposes materials to common cleaning agents and disinfectants to assess compatibility and retention of antimicrobial properties (Munteanu *et al*., 2021). These accelerated tests must be validated against real-world performance data to ensure accurate prediction of service life.

5.3 Strategies for Enhanced Durability

Several approaches have been developed to enhance the durability of bio-based antimicrobial building surfaces. Chemical crosslinking of polymer matrices can improve moisture resistance and mechanical stability while maintaining antimicrobial activity (Souza *et al.*, 2023). Incorporation of UV stabilizers and antioxidants can protect bio-based materials from photodegradation and oxidative damage. Microencapsulation and controlled release systems can protect sensitive antimicrobial compounds while providing sustained activity over extended periods (Aranaz *et al.*, 2021). These systems can be designed to respond to specific environmental triggers or provide time-controlled release profiles. Surface texturing and hierarchical structuring can enhance durability by protecting active sites from mechanical wear while improving antimicrobial contact.

Table 2: Durability Assessment Methods for Bio-based Antimicrobial Building Surfaces.

Test Method	Standard Reference	Duration	Key Parameters	Acceptance Criteria	Reference Sources
UV exposure	ASTM G154	1000-2000 hours	Irradiance, temperature, humidity	<50% activity loss	Abutu *et al.*, 2025
Humidity cycling	ASTM D4585	500-1000 cycles	RH range, temperature	<30% activity loss	Munteanu *et al.*, 2021
Thermal cycling	ASTM D4498	100-300 cycles	Temperature range, dwell time	<25% activity loss	Motamedi *et al.*, 2025
Abrasion resistance	ASTM D4060	1000-5000 cycles	Load, wheel type	<75% activity loss	AlQurashi *et al.*, 2025
Chemical resistance	ASTM D1308	24-168 hours	Chemical type, concentration	<40% activity loss	Souza *et al.*, 2023
Real-world exposure	Site-specific	1-5 years	Environmental monitoring	<60% activity loss	Brandelli, 2024

6. Safety Assessment and Regulatory Considerations

6.1 Toxicological Evaluation Framework

The safety assessment of bio-based nanomaterials for building applications requires comprehensive toxicological evaluation that considers both acute and chronic exposure scenarios. The framework must address potential exposure routes including inhalation of airborne particles, dermal contact with surfaces, and indirect exposure through material degradation products (Ebenezer *et al.*, 2025; Ogunsona *et al.*, 2025a). While bio-based materials are generally considered safer than synthetic alternatives, their nanoscale properties can alter biological interactions and require specific safety evaluation protocols. Cytotoxicity testing using standardized cell culture methods provides initial screening for potential adverse effects. Genotoxicity assays evaluate potential for DNA damage, while inflammatory response studies assess immune system activation (Munteanu *et al.*, 2021; Ogunsona *et al.*, 2025b). Advanced testing methods including organ-on-chip models and in vivo studies may be required for comprehensive safety assessment of novel nanomaterials.

6.2 Occupational Health and Safety

Workers involved in manufacturing, installation, and maintenance of bio-based antimicrobial building materials may face occupational exposure risks that require appropriate safety measures. Inhalation exposure during powder handling and spray application represents the primary concern, particularly for nanoparticulate materials that can penetrate deep into respiratory tissue (Kurul *et al.*, 2025). Engineering controls including ventilation systems, enclosed processing equipment, and personal protective equipment are essential for minimizing worker exposure. Training programs must be developed to educate workers about potential risks and appropriate safety procedures. Material safety data sheets must provide comprehensive information about hazard identification, exposure controls, and emergency procedures (Agnihotri and Dhiman, 2017). Regular health monitoring may be appropriate for workers with significant exposure potential.

6.3 Environmental Impact Assessment

Environmental impact assessment of bio-based antimicrobial building materials must consider their entire life cycle from raw material extraction through end-of-life disposal. While bio-based materials generally have lower environmental impacts than synthetic alternatives, their production, use, and disposal can still affect ecosystems (Ikeh, 2024). Leaching studies evaluate potential for antimicrobial agents to migrate from building materials into surrounding environments. Biodegradation studies assess the fate of bio-based materials in various environmental compartments including soil, water, and sediment. Ecotoxicity testing evaluates potential effects on non-target organisms including beneficial bacteria, aquatic species, and terrestrial wildlife (Abd El-Hack *et al.*, 2020). Life cycle assessment methodologies can quantify environmental impacts and identify opportunities for improvement.

6.4 Regulatory Framework and Standards

The regulatory landscape for bio-based antimicrobial building materials involves multiple agencies and standards organizations worldwide. Recent advances and challenges in metal-based antimicrobial materials highlight the need for comprehensive regulatory frameworks to combat antibiotic resistance (Parvin *et al.*, 2025). Despite availability of classical antibiotic drugs, bacterial infections continue to represent significant and urgent threats to global human health. International standards organizations including ASTM International, ISO, and JIS have developed testing methods and performance standards for antimicrobial building materials. Harmonization of regulatory requirements across different jurisdictions remains a challenge for global market development (Motamedi *et al*., 2025). Emerging nanotechnology-specific regulations may impose additional requirements for nanomaterial characterization and safety assessment.

7. Current Research Trends and Innovations

7.1 Advanced Fabrication Techniques

Recent advances in fabrication techniques have enabled more precise control over bio-based nanomaterial properties and performance characteristics. Electrospinning technology allows production of nanofibrous materials with controlled porosity and surface area that enhance antimicrobial activity (Kumara *et al*., 2023; Motamedi *et al*., 2025). Spray drying and supercritical fluid processing enable production of nanoparticles with narrow size distributions and improved stability. Layer-by-layer assembly techniques can create precisely controlled multilayer coatings with tailored properties and sustained release characteristics (Parvin *et al*., 2025). The development of smart theranostic systems composed of carboxymethyl chitosan coated gold-silver nanoparticles demonstrates advanced fabrication approaches that combine multiple functionalities in single systems.

7.2 Smart and Responsive Systems

The development of smart antimicrobial systems that respond to environmental conditions or microbial presence represents an emerging research frontier. pH-responsive systems can provide targeted antimicrobial activity when acidic conditions indicate microbial growth (Wang *et al*., 2017). Temperature-responsive materials can adjust their release rates based on ambient conditions or metabolic heat generation from microbial activity. MXenes represent wonderful nanomaterials with antibacterial properties that can be engineered for smart responsive applications (Saad *et al*., 2024). Increasing bacterial infections and growing resistance to available drugs pose serious threats to human health and the environment, driving development of advanced responsive antimicrobial systems.

7.3 Computational Design and Modeling

Computational approaches are increasingly being used to design and optimize bio-based antimicrobial materials. Molecular dynamics simulations can predict interactions between antimicrobial agents and microbial targets, enabling rational design of more effective formulations (Agnihotri *et al*., 2017). Machine learning algorithms can identify optimal combinations of materials and processing conditions based on large datasets of experimental results. Progress in antibacterial applications of nanozymes shows that some researchers have studied silver nanoclusters with ultra-small sizes as antibacterial materials (Yilmaz *et al*., 2023). Computational modeling can predict the distribution and release of antimicrobial agents from building material matrices under various environmental conditions, accelerating development cycles and reducing extensive experimental testing requirements.

8. Commercial Applications and Case Studies

8.1 Healthcare Facility Applications

Healthcare facilities represent the largest market for antimicrobial building materials due to strict infection control requirements and high-risk patient populations. Chitosan-based antimicrobial coatings have been successfully implemented in hospital patient rooms, operating theaters, and intensive care units (Munteanu *et al*., 2021). Case studies demonstrate significant reductions in healthcare-associated infections when comprehensive antimicrobial surface treatments are implemented. In vitro biological and antimicrobial properties of chitosan-based bioceramic coatings show significant promise for healthcare applications. Chitosan-coated nanoparticles exhibited significant antimicrobial effects against gram-negative bacteria, which are particularly problematic in healthcare settings (Kurul *et al*., 2025). Long-term studies demonstrate sustained antimicrobial efficacy over extended periods with minimal maintenance requirements.

8.2 Educational Institution Applications

Schools and universities have implemented bio-based antimicrobial building materials to reduce disease transmission among student populations. Cellulose nanocrystal-based coatings applied to high-touch surfaces including door handles, desks, and railings have demonstrated effective reduction of common respiratory and gastrointestinal pathogens (Brandelli, 2024). Student absenteeism rates have shown measurable improvement in facilities with comprehensive antimicrobial surface treatments. The safety profile of bio-based materials makes them particularly suitable for educational environments where children may have increased exposure through hand-to-mouth contact. Long-term studies have confirmed absence of adverse health effects while maintaining effective antimicrobial performance throughout academic years (Souza *et al*., 2023).

8.3 Food Processing and Restaurant Applications

Food processing facilities and commercial kitchens present unique challenges for antimicrobial building materials due to harsh cleaning protocols and regulatory requirements for food safety. Bio-based antimicrobial systems have been successfully integrated into food processing environments while maintaining compliance with food safety regulations (Wang *et al*., 2021). Protein-based nanomaterials have shown particular compatibility with food processing requirements due to their generally recognized as safe status. The use of essential oils in chitosan or cellulose-based materials for production of active food packaging solutions has grown steadily, following trends toward sustainable systems with additional functionality (Ang *et al*., 2025). Restaurant applications have focused on high-touch surfaces and food preparation areas where traditional antimicrobial treatments may pose food safety concerns.

9. Economic Considerations and Market Analysis

9.1 Cost Analysis and Economic Viability

The economic viability of bio-based antimicrobial building materials depends on multiple factors including raw material costs, processing complexity, performance characteristics, and market demand. While bio-based materials may have higher initial costs compared to conventional alternatives, their environmental benefits and safety profiles can justify premium pricing in specific market segments (Ikeh, 2024). Life cycle cost analysis must consider not only material costs but also installation, maintenance, and replacement expenses over building service life. Manufacturing scale significantly impacts cost structures, with larger production volumes enabling economies of scale and reduced unit costs. Investment in specialized processing equipment and quality control systems requires careful economic analysis to ensure market viability (Abd El-Hack *et al*., 2020). Government incentives and regulations promoting sustainable building materials can improve economic attractiveness of bio-based alternatives.

9.2 Market Trends and Projections

The global market for antimicrobial building materials has experienced rapid growth following increased awareness of infection control and indoor air quality issues. Bio-based antimicrobial materials represent a growing segment within this market, driven by sustainability concerns and regulatory pressures to reduce synthetic chemical usage (Parvin *et al*., 2025). Market research indicates continued growth potential in healthcare, education, and commercial building sectors. Regional market variations reflect different regulatory environments, cultural preferences, and economic conditions. European markets show strong preference for bio-based materials due to strict environmental regulations and consumer awareness. Developing markets present growth opportunities but may prioritize cost over sustainability considerations (Motamedi *et al*., 2024).

9.3 Supply Chain Considerations

The supply chain for bio-based antimicrobial building materials involves multiple stakeholders including raw material suppliers, processing facilities, distributors, and end users. Raw material availability and quality consistency represent critical success factors that require careful supplier management and quality control systems (Brandelli, 2024). Seasonal variations in agricultural raw materials can affect supply stability and pricing. Geographic distribution of raw materials may require global supply chains that increase transportation costs and environmental impacts. Local sourcing strategies can reduce these impacts while supporting regional economic development. Supply chain resilience has become increasingly important following recent global disruptions that affected material availability and pricing (Parvin and Hoque, 2022).

10. Future Directions and Research Opportunities

10.1 Technology Development Priorities

Future research priorities should focus on addressing current limitations while exploring new opportunities for bio-based antimicrobial building materials. Enhanced durability remains a critical need, particularly for exterior applications and high-wear environments (Abutu *et al*., 2025). Development of hybrid systems combining multiple antimicrobial mechanisms could provide synergistic effects and broader spectrum activity. Scale-up and manufacturing optimization represent important areas for technology development. Continuous processing methods and automated quality control systems are needed to reduce costs and improve consistency (Ingle *et al*., 2025). Integration with emerging building technologies including smart building systems and advanced material systems offers new application opportunities.

10.2 Regulatory and Standards Development

Harmonization of regulatory requirements across different jurisdictions would facilitate global market development and reduce compliance costs. Development of nanotechnology-specific regulations and testing protocols is needed to address unique characteristics of bio-based nanomaterials (Sahiner *et al*., 2022). Standardized performance testing methods specifically designed for bio-based materials would improve market confidence and facilitate product comparison. International cooperation in regulatory development could accelerate market adoption while ensuring appropriate safety protections. Public-private partnerships may be effective for developing testing methods and performance standards that reflect both technical capabilities and market needs (Agnihotri and Dhiman, 2017).

10.3 Sustainability and Circular Economy Integration

Future development should emphasize integration with circular economy principles including renewable raw material sourcing, recyclability, and end-of-life material recovery. Bio-refinery concepts that utilize agricultural and forestry waste streams for nanomaterial production could improve sustainability while reducing costs (Orsuwan and SOthornit, 2018). Development of biodegradable formulations that maintain performance while facilitating end-of-life disposal represents an important research opportunity. Life cycle assessment methodologies specifically designed for bio-based nanomaterials would enable more accurate environmental impact evaluation and identification of improvement opportunities. Integration with carbon footprint reduction goals and sustainable building certification programs could drive market adoption (Abd El-Hack *et al*., 2020).

11. CONCLUSIONS

Bio-based nanomaterials represent a promising and rapidly evolving field for antimicrobial building surface applications. This comprehensive review has examined the current state of research and development across multiple material categories, performance characteristics, and application areas. Key findings indicate that bio-based nanomaterials can provide effective antimicrobial activity while offering environmental and safety advantages compared to conventional synthetic alternatives. Chitosan-based nanomaterials have demonstrated the most mature technology development with proven commercial applications in healthcare and educational facilities. Essential oil-loaded nanosystems show strong potential for applications where pleasant odor characteristics are valued alongside antimicrobial efficacy. Cellulose-based systems offer excellent mechanical properties and compatibility with existing building material manufacturing processes.

Durability remains a critical challenge that requires continued research focus. While accelerated testing methods provide valuable insights, long-term real-world studies are needed to validate performance predictions and optimize formulation strategies. Integration of UV stabilizers, chemical crosslinking, and controlled release systems offer promising approaches for enhanced durability. Safety assessment protocols specifically designed for bio-based nanomaterials are essential for regulatory approval and market confidence. While bio-based materials generally present lower risk profiles than synthetic alternatives, their nanoscale properties require careful evaluation of exposure pathways and biological interactions. Occupational health and safety considerations are particularly important during manufacturing and installation activities. Economic viability depends on achieving cost competitiveness while providing superior performance or environmental benefits that justify premium pricing. Manufacturing scale-up and supply chain optimization represent critical success factors for market development. Government policies and regulations promoting sustainable building materials can accelerate market adoption.

Future research opportunities include development of smart responsive systems, integration with emerging building technologies, and optimization of circular economy approaches. International cooperation in regulatory development and standards harmonization would facilitate global market growth while ensuring appropriate safety protections. The successful commercialization of bio-based antimicrobial building materials requires continued collaboration between researchers, manufacturers, regulators, and end users. Addressing current technical challenges while maintaining focus on sustainability and safety will enable these materials to make significant contributions to healthier built environments and reduced environmental impact.

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No conflicts of interest among authors

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