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REVIEW

Current developments in coating technologies: Components, workings, and prospects for the food and biomedical industries

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ABSTRACT

Coating technologies are critical to advancing sustainability, safety, and functionality in the food and biomedical industries, yet a notable gap persists in the lack of cross-sectoral comparative analyses that leverage shared technological principles. This review synthesizes recent advancements in coating materials, fabrication techniques, characterization methods, and functional properties for both sectors, highlighting their role in addressing global challenges. In biomedical applications, polymeric coatings like PLGA and bioactive hydroxyapatite enhance implant durability, enable controlled drug release, and improve biocompatibility, while antimicrobial and stimuli-responsive coatings prevent infections and adapt to physiological conditions. In the food industry, edible coatings from polysaccharides, proteins, and lipids extend shelf life and reduce environmental impact, with active coatings incorporating antimicrobial extracts and biodegradable nanocomposites enhancing preservation. Fabrication techniques have evolved from conventional dip and spray methods to advanced layer-by-layer assembly and 3D printing, offering precise control over coating properties. Characterization focuses on adhesion, wettability, and biocompatibility to ensure performance and safety compliance. Innovations include zwitterionic antifouling surfaces and smart packaging indicators, though challenges remain in scalability, toxicity evaluation, and regulatory harmonization. Future directions emphasize AI-driven design, multifunctional self-healing coatings, and circular economy principles to foster sustainability. Cross-sector collaboration promises to accelerate innovation, enabling transformative solutions for personalized medicine and sustainable food systems, addressing regulatory and scalability hurdles through shared expertise.

KEY WORDS

Coating technologies; Biomedical implants; Antimicrobial properties; Edible coatings; Sustainable packaging.

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Introduction

The global landscape of surface modification technologies has undergone a revolutionary transformation over the past decade, with coating technologies emerging as a cornerstone for innovation across multiple industrial sectors [1]. Among these, the food and biomedical industries represent two of the most dynamic and rapidly evolving domains where advanced coating solutions are not merely beneficial but essential for addressing contemporary challenges in sustainability, safety, and enhanced functionality [2,3]. The increasing demand for safer, more durable, and environmentally conscious products has catalyzed unprecedented research efforts in developing sophisticated coating materials and application techniques that can meet the stringent requirements of these critical industries [4].

In the biomedical sector, the integration of advanced coating technologies has become indispensable for modern healthcare applications [5]. The current healthcare landscape demands medical devices and implants that not only demonstrate exceptional biocompatibility but also exhibit multifunctional capabilities such as controlled drug release, antimicrobial properties, and enhanced mechanical performance. Traditional uncoated medical devices often face significant challenges, including bacterial colonization, immune system rejection, and suboptimal integration with surrounding tissues [3,6]. These limitations have driven researchers and manufacturers to develop innovative coating solutions that can transform inert substrates into bioactive surfaces capable of promoting healing, preventing infections, and improving patient outcomes [7].

Similarly, the food industry is experiencing a paradigm shift towards sustainable packaging solutions and advanced preservation technologies. The growing environmental consciousness among consumers, coupled with increasingly stringent regulatory frameworks aimed at reducing plastic waste, has created an urgent need for alternative coating solutions [8,9]. Traditional petroleum-based packaging materials are being challenged by innovative edible coatings, biodegradable barrier systems, and active packaging technologies that can extend shelf life while minimizing environmental impact [10]. These developments are particularly crucial given the global food security challenges and the imperative to reduce the estimated 1.3 billion tons of food waste generated annually worldwide.

Despite the significant progress made in both sectors, a comprehensive analysis of the current literature reveals several critical gaps that this review aims to address. First, while numerous studies have focused on individual coating applications within specific industries, there remains a notable lack of comparative analysis that examines the parallel development trajectories and shared technological principles between food and biomedical coating applications [11,12]. This cross-sectoral perspective is increasingly important as both industries face similar challenges related to sustainability, regulatory compliance, and the need for multifunctional [11,13].

Second, existing reviews have predominantly focused on either material properties or application methods in isolation, without providing an integrated understanding of how

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fabrication techniques influence functional performance across different use cases [14]. The relationship between manufacturing processes, material selection, and end-use performance represents a complex interdisciplinary challenge that requires systematic analysis to guide future research directions and industrial implementation strategies [15].

Third, the rapidly evolving regulatory landscape in both industries has created new challenges and opportunities that have not been adequately addressed in current literature. The emergence of nanotechnology-based coatings, smart responsive materials, and novel bioactive compounds has outpaced regulatory frameworks, creating uncertainty for manufacturers and researchers alike [16,17]. Understanding these regulatory challenges and their implications for future technological development is crucial for translating laboratory innovations into commercially viable products.

Furthermore, the convergence of materials science, nanotechnology, and biotechnology has opened new avenues for developing next-generation coating solutions that were previously unimaginable [18]. The integration of artificial intelligence and machine learning in coating design and optimization, the development of self-healing materials, and the emergence of truly multifunctional surfaces represent frontier areas that require systematic investigation and documentation [19].

This comprehensive review addresses these identified gaps by providing an integrative analysis of current developments in coating technologies for both food and biomedical applications. By examining common principles, shared challenges, and parallel innovation trajectories, this work offers a unique perspective that can inform future research strategies and facilitate knowledge transfer between these traditionally separate domains [20]. The review synthesizes recent advances in materials science, fabrication techniques, characterization methods, and functional properties while providing critical analysis of regulatory challenges and future opportunities [11]. Through this integrated approach, we aim to provide researchers, engineers, and industry professionals with the comprehensive understanding necessary to advance the next generation of coating technologies that will define the future of both food and biomedical industries [13].

Coating Materials in Biomedical Applications

Polymeric coatings

Synthetic polymers have emerged as the backbone of modern biomedical coating technologies, with poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and polyethylene glycol (PEG) representing the most widely utilized materials for orthopedic implants, wound dressings, and drug-eluting stents [21,22]. These polymeric systems offer unprecedented control over biodegradation kinetics, allowing researchers to engineer materials that degrade at predetermined rates while simultaneously releasing therapeutic compounds in a controlled manner [23]. The versatility of these polymers lies in their tunable properties, where molecular weight, copolymer ratios, and cross-linking density can be precisely adjusted to achieve desired release profiles and mechanical characteristics [21]. PLGA, in particular, has garnered significant attention due to its FDA-approved status and well-established safety profile, making it an ideal candidate for drug delivery applications where both efficacy and biocompatibility are paramount concerns [22].

Bioactive and biomimetic coatings

The development of bioactive and biomimetic coating systems represents a sophisticated approach to enhancing tissue integration and cellular adhesion through the strategic incorporation of naturally occurring biological components. Collagen, fibrin, hydroxyapatite, and gelatin-based coatings have demonstrated a remarkable ability to facilitate tissue integration by creating microenvironments that closely mimic the natural extracellular matrix [24]. These biomimetic approaches go beyond simple biocompatibility to actively promote healing processes and reduce foreign-body responses that commonly plague conventional implant materials. Hydroxyapatite coatings, specifically, have revolutionized orthopedic and dental implant technologies by providing a calcium phosphate surface that promotes direct bone apposition and long-term osseointegration [25,26]. The success of these materials stems from their ability to present appropriate biochemical cues that guide cellular behavior and tissue remodeling processes.

Antimicrobial and antifouling coatings

The persistent challenge of bacterial colonization on medical device surfaces has driven the development of sophisticated antimicrobial coating systems incorporating graphene oxide, quaternary ammonium salts, zinc oxide, and silver nanoparticles [27,28]. These materials function through multiple mechanisms, including direct bacterial membrane disruption, generation of reactive oxygen species, and interference with essential metabolic processes. Complementing these antimicrobial approaches, zwitterionic and PEG-based coatings provide antifouling properties by creating hydrated surface layers that resist protein adsorption and subsequent bacterial attachment [28]. The combination of these two strategies has proven particularly effective in developing surfaces that not only kill existing bacteria but also prevent initial colonization events that lead to biofilm formation [29]. Recent advances have focused on developing coatings that can distinguish between pathogenic microorganisms and beneficial cellular interactions, representing a more nuanced approach to infection control [30].

Stimuli-responsive coatings

The emergence of stimuli-responsive or "smart" coating systems has opened new possibilities for developing medical devices that can adapt their behavior in response to specific environmental conditions [31]. These intelligent materials are designed to respond to physiological stimuli such as pH changes, temperature variations, or enzymatic activity, enabling controlled drug release or dynamic alteration of surface properties [32]. The applications of these responsive systems are particularly promising in tissue engineering scaffolds where controlled degradation and cellular guidance are required, implantable devices that need to adapt to changing physiological conditions, and advanced wound healing applications where treatment parameters must be adjusted based on healing progress. The sophistication of these systems continues to evolve, with recent developments incorporating multiple responsive mechanisms that can provide complex, programmable surface behaviors [33]. Table 1 illustrates various coating materials, their key application areas and benefits as recent literature reports.

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Table 1. Different coating materials with their key benefits and application areas as per recent literature.

Coating Material	Application Area	Key Properties / Benefits
PLGA, PCL, PEG	Drug-eluting stents, wound dressings	Biodegradable, tunable drug release
Hydroxyapatite	Orthopedic and dental implants	Promotes bone integration, bioactive
Collagen / Gelatin	Tissue engineering scaffolds	Mimics extracellular matrix, supports cell adhesion
Silver nanoparticles	Catheters, implant surfaces	Broad-spectrum antimicrobial activity
Graphene oxide / MXenes	Sensors, antimicrobial coatings	Conductive, antibacterial, high surface area
Zwitterionic polymers	Antifouling surfaces	Resists protein adsorption and bacterial attachment

Coating Substances in the Food Sector

Edible coatings

The foundation of edible coating technology rests on three primary categories of naturally occurring materials: polysaccharides (including starch, cellulose, and pectin), proteins (such as casein and whey), and lipids (comprising various waxes and oils) [34,35]. These materials offer the unique advantage of being directly consumable with food products, thereby eliminating packaging waste while providing essential barrier and preservation functions. Polysaccharide-based coatings excel in providing structural integrity and moisture barrier properties, with starch-based systems offering excellent film-forming capabilities and pectin providing superior flexibility and clarity [36]. Protein-based edible coatings contribute additional nutritional value while delivering exceptional mechanical strength and gas barrier properties. The integration of lipid components enhances water resistance and provides glossy appearances that improve visual appeal [37]. The synergistic combination of these materials in composite formulations allows for the optimization of specific properties while maintaining the fundamental advantage of complete edibility.

Active coatings

Active coating systems represent a paradigm shift from passive barrier functions to dynamic preservation technologies that actively contribute to food safety and quality maintenance throughout the supply chain. These sophisticated systems incorporate bioactive compounds such as antioxidants, antimicrobials, or nutraceuticals that are released in controlled manner to extend shelf life and enhance nutritional value. Essential oil-based coatings have gained particular attention due to their natural antimicrobial properties and consumer acceptance, while plant extract systems offer both antioxidant and antimicrobial functionalities [38]. Probiotic-containing coatings represent an innovative approach that not only preserves food quality but also delivers beneficial microorganisms that can contribute to consumer health. The development of these active systems requires careful consideration of compound stability, release kinetics, and sensory impact to ensure that preservation benefits do not compromise food quality or acceptance [39].

Biodegradable coatings

The environmental imperatives driving the packaging industry have accelerated the development of biodegradable coating systems based on materials such as polylactic acid (PLA), polyhydroxybutyrate (PHB), and chitosan. These materials offer promising alternatives to petroleum-based packaging while addressing both environmental concerns and increasingly stringent regulatory requirements for plastic reduction. Chitosan, derived from crustacean shells, has emerged as particularly promising due to its inherent antimicrobial properties, excellent film-forming ability, and complete biodegradability. PLA-based systems provide superior mechanical properties and processing characteristics, making them suitable for more demanding packaging applications. The development of these biodegradable alternatives requires careful balance between environmental benefits, functional performance, and economic viability to achieve widespread commercial adoption [40].

Barrier and functional coatings

Advanced barrier coating systems have evolved to incorporate sophisticated nanomaterials including hybrid organic-inorganic compounds, silica nanoparticles, and nanoclays that dramatically enhance moisture and oxygen barrier properties. These nanocomposite systems achieve superior performance through the creation of tortuous diffusion pathways that significantly reduce permeability while maintaining optical clarity and mechanical flexibility. Different coating materials have been utilized for various applications, as demonstrated in Table 2. The integration of smart sensing technologies has led to the development of coatings that incorporate colorimetric indicators or embedded sensors capable of monitoring spoilage, temperature exposure, or freshness in real-time. These intelligent packaging systems provide valuable information throughout the supply chain, enabling better inventory management and reducing food waste through improved quality assessment capabilities [41].

Table 2. Numerous coating materials, their benefits and applications.

Coating Material	Food Application	Key Properties / Benefits
Chitosan	Fruits, vegetables, seafood	Antimicrobial, film-forming, biodegradable
Starch / Pectin	Bakery and fresh produce	Edible, moisture barrier
Casein / Whey proteins	Dairy and confectionery	Protein-based edible films
Silver nanoparticles	Catheters, implant surfaces	Broad-spectrum antimicrobial activity
Lipid-based wax coatings	Citrus fruits, apples	Water loss prevention, shine
Nano clays / Silica	Packaged foods	Oxygen/moisture barrier, extends shelf life
Plant extracts / Essential oils	Meat, cheese, fresh produce	Natural antioxidants and antimicrobials

Fabrication Techniques

Conventional methods

Traditional coating application methods including spin coating, dip coating, and spray coating continue to serve as

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the foundation for creating uniform thin coatings across diverse substrates in both medical device manufacturing and food processing applications. These well-established techniques offer the advantages of relative simplicity, scalability, and cost-effectiveness, making them particularly attractive for large-scale commercial production. Dip coating provides excellent uniformity and complete surface coverage, making it ideal for complex geometries and irregularly shaped substrates. Spray coating offers rapid application rates and the flexibility to coat large surfaces or multiple items simultaneously, while spin coating delivers exceptional uniformity for flat substrates in research and specialized applications. The maturity of these technologies has led to highly optimized process parameters and quality control methods that ensure consistent coating properties across production runs [42].

Advanced deposition

Layer-by-layer self-assembly techniques have emerged as powerful tools for achieving nanoscale control over coating thickness and composition, enabling the creation of precisely engineered multilayer systems with tailored properties. This approach allows researchers to build complex coating architectures by sequentially depositing alternating layers of oppositely charged materials, creating systems with precisely controlled release kinetics and multifunctional properties. UV-curing and plasma-enhanced deposition methods provide additional capabilities for creating robust adhesion and customizable cross-linking densities that can be precisely tailored to specific application requirements. Plasma treatment offers the unique advantage of creating highly adherent coatings with excellent chemical resistance and sterilization compatibility, making these techniques particularly valuable for critical medical applications where coating integrity is paramount [43].

Emerging additive manufacturing

The integration of additive manufacturing technologies including inkjet printing and 3D printing has opened unprecedented possibilities for creating complex coating designs and gradient structures that were previously impossible to achieve through conventional methods. In biomedical applications, these technologies enable the creation of patient-specific coatings with precisely controlled drug loading profiles and geometric features tailored to individual anatomical requirements. Table 3 illustrates the various recently utilized coating techniques, their usage in biomedical and food processing and advantages. Food industry applications benefit from the ability to create customized edible films with precise concentrations of active compounds distributed in specific patterns or gradients. The flexibility of additive manufacturing allows for the creation of coatings with spatially varying properties, enabling single coating systems that can provide multiple functions across different regions of the same substrate [44].

Table 3. Recently utilized coating techniques, their usage in biomedical and food processing and advantages.

Technique	Biomedical Use Example	Food Use Example	Advantages
Dip-coating	Drug-eluting stents	Edible coatings on fruits	Uniform coating, scalable
Spray-coating	Catheter coatings	Spray application of edible films	Fast, easy to apply to irregular shapes
Spin-coating	Microdevices, biosensors	N/A (less common)	Thin, uniform layers, lab-scale
Layer-by-layer assembly	Multifunctional coatings on implants	Active coatings with bioactives	Nanometer-scale control
Plasma deposition	Antimicrobial layers on implants	Sterilization-friendly surfaces	Strong adhesion, high purity
3D/Inkjet printing	Custom implants, drug layers	Printed edible designs	Tailored patterns, dose control

Functional Properties and Testing

Comprehensive characterization of coating properties represents a critical aspect of both biomedical and food industry applications, requiring sophisticated testing methodologies that can accurately predict real-world performance under diverse operating conditions. Adhesion and mechanical integrity assessment through techniques such as peel testing, scratch resistance evaluation, and nanoindentation provides fundamental insights into coating durability and long-term stability. These mechanical properties directly influence the lifetime and reliability of coated products, making their accurate measurement essential for quality assurance and regulatory compliance. The complexity of these measurements is heightened by the need to simulate realistic use conditions while maintaining standardized test protocols that enable meaningful comparisons between different coating systems [45].

Wettability and surface energy characterization through contact-angle measurements provides valuable predictive capabilities for both biocompatibility and barrier performance assessment. In biomedical applications, surface wettability directly influences protein adsorption patterns and cellular adhesion behavior, making these measurements critical for predicting biological response. Food packaging applications require careful control of wettability to achieve optimal barrier properties and product compatibility. Table 4 demonstrates the properties of the coated materials, their associated standard measurements, and their subsequent requirements in biomedical and food industries. The relationship between surface energy and functional performance represents a complex interplay of chemical composition, surface topography, and environmental conditions that requires sophisticated analysis techniques [46].

Biocompatibility assessment for medical coatings involves comprehensive evaluation protocols including cytotoxicity testing, hemocompatibility analysis, and animal studies that ensure patient safety and regulatory compliance. These biological evaluation methods follow established international standards such as ISO 10993 and require extensive

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documentation and validation. Parallel to biocompatibility requirements, food contact coatings must undergo rigorous safety evaluation including migration testing and extractables analysis to verify compliance with FDA and EFSA regulatory guidelines. These safety assessments require specialized analytical techniques capable of detecting and quantifying potential migrants at extremely low concentration levels [47].

Table 4. Properties of the coated materials, their associated standard measurements, and their subsequent requirements in biomedical and food industries.

Property	Test/Standard	Biomedical Importance	Food Industry Importance
Adhesion	ASTM D3359 cross-cut test	Implant durability	Packaging integrity
Wettability	Contact-angle measurement	Protein adsorption control	Barrier property to moisture
Cytotoxicity	ISO 10993	Ensures patient safety	N/A (but migration testing for safety)
Migration of additives	FDA/EFSA guidelines	N/A	Food safety compliance
Mechanical strength	Nanoindentation / tensile testing	Implant wear resistance	Packaging tear resistance

Recent Innovations

Biomedical sector

Recent breakthrough developments in biomedical coating technologies have focused on creating increasingly sophisticated surface modification systems that address multiple clinical challenges simultaneously. Antifouling and zwitterionic coating systems have demonstrated remarkable success in extending implant lifespan by significantly reducing bacterial attachment and protein adsorption through the creation of highly hydrated surface layers that resist biological fouling. These systems work by creating a bound water layer that acts as a barrier to protein and bacterial adhesion, effectively creating surfaces that remain clean and functional for extended periods in biological environments [48].

Drug-eluting coating technologies have evolved to provide unprecedented control over therapeutic agent release, with biodegradable polymer-coated orthopedic implants and vascular stents now capable of delivering medications over precisely controlled timeframes ranging from days to months. These systems represent a significant advancement in personalized medicine, allowing clinicians to tailor drug delivery profiles to individual patient needs and specific clinical conditions. The integration of multiple therapeutic agents within single coating systems has enabled combination therapies that can address multiple aspects of healing and recovery simultaneously [49].

Nanostructured surface technologies have revolutionized implant integration through the creation of precisely controlled surface topographies that guide cellular behavior and enhance tissue integration processes. Titanium implants featuring nanoscale surface features have demonstrated superior osteointegration compared to conventional smooth surfaces, with the ability to accelerate bone formation and improve long-term stability. These advances represent a convergence of materials science, nanotechnology, and biological understanding that continues to push the boundaries of what is possible in implant technology [50].

Food sector

Innovation in food coating technologies has been driven by consumer demands for safer, more sustainable, and higher-quality food products, leading to the development of intelligent packaging systems that actively contribute to food safety and quality maintenance. Smart coating systems incorporating temperature or pH indicators provide real-time information about storage conditions and spoilage status, enabling better inventory management and reducing food waste through improved quality assessment capabilities. These systems represent a significant advancement over traditional static packaging by providing dynamic information throughout the supply chain [51].

Edible nanocoating technologies have emerged as powerful tools for protecting sensitive compounds such as vitamins, probiotics, and flavouring agents while maintaining their bioactivity and sensory properties. These ultrathin coating systems provide targeted protection against environmental stressors such as oxygen, moisture, and light while being completely transparent to consumers. The development of these systems requires sophisticated understanding of compound stability, release mechanisms, and sensory impact to ensure that protection benefits do not compromise food quality or consumer acceptance [52].

Natural extract-based antimicrobial coating systems utilizing essential oils, chitosan, and plant polyphenols have gained significant traction due to increasing consumer preference for natural preservation methods and growing concerns about synthetic additives. These systems provide effective antimicrobial activity while contributing to the overall nutritional value of food products and meeting clean-label requirements that are increasingly important in consumer purchasing decisions [53].

Challenges and Regulatory Issues

The implementation of advanced coating technologies faces significant challenges related to safety assessment and toxicity evaluation, particularly concerning nanomaterials and novel bioactive compounds that lack extensive historical safety data. Regulatory agencies worldwide are grappling with the development of appropriate testing protocols and safety standards for these emerging technologies, creating uncertainty for manufacturers and researchers. The complexity of these assessments is heightened by the need to evaluate not only the safety of individual coating components but also their potential interactions with biological systems and food matrices over extended periods [54].

Scale-up and cost considerations represent major hurdles in translating laboratory-developed coating technologies into commercially viable products. Many promising coating formulations developed at laboratory scale face significant technical and economic challenges when transitioning to industrial production levels. The need to maintain quality and performance standards while achieving cost-effective production requires careful optimization of manufacturing processes, raw material selection, and quality control systems. These challenges are particularly acute for specialty applications where high performance requirements must be balanced against economic constraints [55].

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Standardization efforts face the challenge of developing testing protocols and performance standards that can accommodate the diverse range of coating technologies while providing meaningful performance comparisons. The lack of harmonized international standards creates barriers to global market access and complicates regulatory compliance efforts. Different regional approaches to safety assessment and performance evaluation create additional complexity for manufacturers seeking to develop products for global markets [56].

Regulatory compliance requirements continue to evolve as new technologies emerge and safety concerns are identified. Food-contact coating systems must demonstrate compliance with increasingly stringent migration limits established by regulatory agencies such as EFSA and FDA, requiring sophisticated analytical capabilities and extensive documentation. Medical device coatings face similarly complex regulatory pathways that require comprehensive safety and efficacy demonstrations according to standards such as FDA premarket approval processes and ISO 10993 biological evaluation requirements [57].

Coating innovations and environmental impact

The integration of artificial intelligence and machine learning technologies is poised to revolutionize coating development and optimization processes by enabling rapid screening of material combinations, prediction of performance characteristics, and acceleration of regulatory approval processes. These computational approaches can significantly reduce development time and costs while improving the likelihood of successful commercial implementation. Machine learning algorithms trained on extensive databases of coating properties and performance data can identify promising material combinations and predict optimal processing parameters with unprecedented accuracy [58].

The development of truly multifunctional coating systems represents one of the most promising areas for future advancement, with researchers working to integrate multiple capabilities, including self-healing properties, active compound release, environmental sensing, and adaptive surface properties into single coating systems. These advanced materials will enable the creation of smart packaging systems that can respond to changing conditions and medical devices that can adapt their behaviour based on physiological needs [59].

Circular economy principles are driving the development of coating systems that support recyclability, biodegradability, and resource recovery, particularly important for food packaging applications where environmental impact is a growing concern. The design of coatings that can be easily separated during recycling processes or that biodegrade completely without harmful residues represents a significant technical challenge that requires innovative approaches to material selection and system design.

Cross-sector collaboration between food and biomedical industries is creating opportunities for knowledge transfer and technology sharing that can accelerate innovation in both sectors. The potential for using edible biopolymer systems in drug delivery applications or adapting sterilization technologies from biomedical applications for food processing represents exciting areas for future development that can benefit from shared research efforts and combined expertise [60].

Conclusions

The comprehensive analysis presented in this review demonstrates that coating technologies in the food and biomedical industries are undergoing a period of unprecedented innovation and convergence, driven by the critical need for enhanced sustainability, safety, and multifunctional performance. The evolution from simple protective barriers to sophisticated, responsive systems capable of active therapeutic delivery and real-time monitoring represents a fundamental transformation in how we approach surface modification and materials engineering. This technological revolution is being enabled by remarkable advances in materials science, nanotechnology, and digital fabrication techniques that continue to expand the boundaries of what is achievable in coating applications.

The biomedical sector has witnessed remarkable progress in developing coatings that not only provide biocompatibility but actively promote healing, prevent infections, and deliver therapeutic compounds with precise temporal and spatial control. The emergence of stimuli-responsive systems that can adapt their behavior based on physiological conditions represents a significant step toward truly personalized medical treatments. Similarly, the food industry has embraced coating technologies as essential tools for addressing global challenges related to food security, packaging waste reduction, and consumer health, with innovations ranging from edible preservation systems to intelligent packaging that provides real-time quality information.

The parallel development trajectories observed in both industries reveal common underlying principles and shared technological challenges that suggest significant opportunities for cross-sector collaboration and knowledge transfer. Both sectors face similar imperatives related to sustainability, regulatory compliance, and the need for multifunctional surface properties, indicating that collaborative research efforts could accelerate innovation while reducing development costs and timelines. The convergence of these industries is particularly evident in areas such as biodegradable materials development, antimicrobial system design, and smart responsive technologies where common scientific principles can be applied to diverse applications.

However, significant challenges remain in translating laboratory innovations into commercially viable products that can meet the stringent safety, performance, and cost requirements of these demanding industries. The complexity of regulatory approval processes, the technical difficulties associated with large-scale manufacturing, and the need for standardized testing protocols continue to present barriers to widespread adoption of advanced coating technologies. Addressing these challenges will require sustained collaborative efforts between academic researchers, industry partners, and regulatory agencies to develop appropriate frameworks for innovation while ensuring public safety and environmental protection.

Future Scopes

The future of coating technologies in food and biomedical applications is poised for transformative growth across multiple dimensions that will reshape these industries over

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the coming decades. The integration of artificial intelligence and machine learning in coating design and development processes promises to accelerate innovation by enabling rapid virtual screening of material combinations, prediction of long-term performance characteristics, and optimization of manufacturing processes. These computational approaches will significantly reduce development timelines while improving the probability of successful commercial implementation, making advanced coating technologies more accessible to smaller companies and specialized applications.

The development of truly autonomous coating systems represents perhaps the most exciting frontier in this field, with future coatings expected to incorporate self-healing capabilities, adaptive release mechanisms, and real-time diagnostic functions within single integrated systems. In biomedical applications, these systems could provide personalized therapeutic delivery that adjusts drug release rates based on individual patient response, while food applications could feature packaging that automatically adjusts barrier properties based on environmental conditions and product requirements.

Sustainability considerations will drive the development of next-generation coating systems based on circular economy principles, with emphasis on materials that can be easily recycled, completely biodegraded, or even consumed as part of the product. The emergence of bio-based coating materials derived from agricultural waste streams and renewable resources will create new opportunities for sustainable coating solutions while supporting rural economies and reducing dependence on petroleum-based materials.

The convergence of nanotechnology, biotechnology, and digital manufacturing will enable the creation of coatings with unprecedented precision and complexity, including systems that can deliver multiple therapeutic agents simultaneously, provide real-time health monitoring capabilities, or create food packaging that actively communicates with supply chain management systems. These advances will require new regulatory frameworks, standardized testing protocols, and international cooperation to ensure safe and effective implementation across global markets.

Cross-industry collaboration will become increasingly important as the boundaries between food and biomedical applications continue to blur, with opportunities for shared research, technology transfer, and combined regulatory approaches that can benefit both sectors. The potential for creating universal coating platforms that can be adapted for multiple applications will drive efficiency improvements and cost reductions while accelerating the pace of innovation across both industries.

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