

Research article

Bionanotechnology and Biomaterials: An updated review in environmental, Food and biomedical applications

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Abstract The global push for improved food quality, safety, and sustainability has led to the integration of cutting-edge technologies within the food sector. Among these, bionanotechnology and biomaterials have proven to be powerful innovations with diverse industrial uses. Bionanotechnology facilitates the creation of nanoscale devices such as sensors, antimicrobial surfaces, and controlled-release systems that contribute to extending shelf life and maintaining food integrity. Biomaterials, on the other hand, particularly those sourced from natural and biodegradable origins are increasingly used in producing smart packaging, edible coatings, and value added food ingredients aimed at reducing environmental impact. The combination of these technologies supports global objectives related to food sustainability, traceability, and enhanced consumer trust. Nonetheless, challenges such as safety concerns, unclear regulations, and public skepticism must be addressed through continued research and regulatory development. This paper aims to explore the roles, advantages, and limitations of bionanotechnology and biomaterials in modern food and biomedical systems, focusing on innovation, risk management, and sustainable development.

Keywords: Bionanotechnology, Biomaterials, Nanoscale Sensors, Nano-enabled Systems, Functional Food Components

1.0. Introduction

Bionanotechnology is an interdisciplinary field that merges the principles of biology, nanoscience, chemistry, and engineering to design and develop nanoscale devices and systems for a wide range of applications [1]. It particularly emphasizes the use of biological molecules such as DNA, proteins, and cells as functional materials to

create innovative nanodevices. This field harnesses the unique properties that emerge at the nanoscale, such as increased surface-to-volume ratios, quantum effects, and enhanced mechanical, optical, and electrical behaviors [2]. The ability to manipulate biological structures at the molecular and atomic levels opens new frontiers in science and technology, especially for applications where precision,

miniaturization, and biocompatibility are required. Bionanotechnology is driving transformative developments in medicine, food, agriculture, environmental remediation, and renewable energy [3]. Bionanotechnology is grounded in a comprehensive understanding of molecular biology and nanomaterials science. Figure 1 will illustrate bionanotechnology. The field heavily relies on advanced characterization tools such as transmission electron microscopy (TEM), atomic force microscopy (AFM), and scanning tunneling microscopy (STM) for imaging and manipulating nanostructures [4]. Additionally, fabrication techniques such as molecular self-assembly, lithography, and biomimetic synthesis are used to construct functional nanostructures from the bottom up [5]. Biological systems serve as models and materials in bionanotechnology. Nature's nanosystems, such as ribosomes and viral capsids, display highly efficient, self-organizing properties that researchers aim to replicate or harness for technological purposes [6]. For example, DNA origami is used to build complex nanoscale architectures that can be applied in diagnostics and drug delivery [7].

The global food sector is rapidly evolving in response to increasing demands for safer, more nutritious, and environmentally sustainable food products. With rising population levels, climate concerns, and challenges surrounding food security, the industry is turning toward scientific innovations to enhance production and safety standards. Among the most promising developments are bionanotechnology and biomaterials, which are being applied to transform how food is manufactured, preserved, packaged, and distributed [8]. These innovations integrate nanoscience with biology and materials engineering to provide intelligent, efficient, and eco-friendly solutions to persistent problems in food systems. Bionanotechnology, a fusion of nanoscience and biotechnology, enables the manipulation of materials at the molecular or atomic level to create systems with enhanced or novel functions. In food applications, this has led to the emergence of nano-based technologies such as smart packaging, nanosensors for real-time spoilage detection, and nanocarriers for

controlled nutrient release [9]. Biomaterials, on the other hand, are materials derived from natural or synthetic sources that are designed to interact safely with biological systems. These include biopolymers such as cellulose, chitosan, and polylactic acid (PLA), which are now being employed in food packaging and edible coatings to reduce environmental impact and extend product shelf life [10]. Bionanotechnology refers to the use of nanoscale structures (typically less than 100 nano meters in size) in biological or biocompatible applications. In food science, it includes systems that improve nutrient stability, enable precise delivery of functional ingredients, or detect microbial spoilage through embedded nanosensors [11]. These technologies enable high sensitivity and specificity in monitoring and controlling food quality parameters. Advantages of Bionanotechnology: Specificity; Biological molecules provide target-specific interactions, enhancing the precision of diagnostic and therapeutic tools [12]. Biocompatibility; Bio-based nanomaterials often integrate well with living tissues, reducing immune responses [13]. Environmental Sustainability; Many bionanomaterials are biodegradable and derived from renewable resources. Enhanced Efficiency; Nanostructures offer greater surface area and reactivity, improving catalytic and sensing performance. Ethical, Safety, and Regulatory Considerations: While bionanotechnology promises significant benefits, it also raises ethical and safety concerns. Nanoparticles can accumulate in organs and tissues, posing unknown risks to human health [14]. Additionally, the environmental fate of these particles and their long-term impacts remain poorly understood. Biomaterials are materials that can safely interact with living systems, often obtained from renewable sources or designed to be biodegradable. In food contexts, biomaterials serve as alternatives to traditional synthetic packaging materials. They are used to develop edible films, biodegradable wraps, and coatings in fused with active compounds such as antioxidants or antimicrobials, helping improve food safety and environmental sustainability [15]. The integration of bionanotechnology and biomaterials into food systems addresses several critical industry

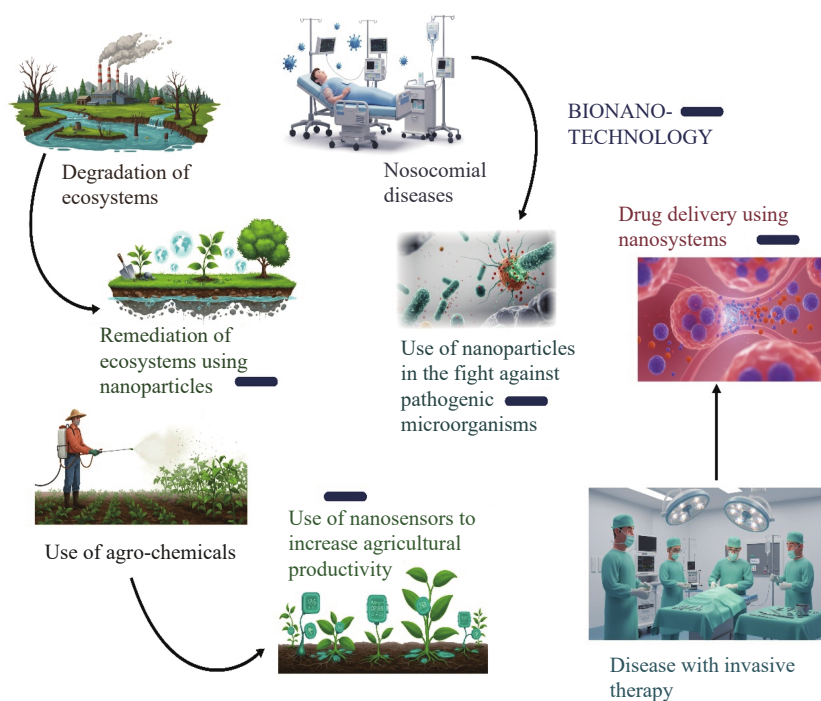


Figure 1. Overview of Bionanotechnology [30].

challenges. Contamination, spoilage, and packaging waste are leading causes of post-harvest food loss and health risks. Traditional packaging made from petroleum based plastics contributes significantly to pollution and lacks functionalities like antimicrobial protection or real-time monitoring. In contrast, bio-based and nanoscale innovations offer smart and greener alternatives. For instance, nanoencapsulation techniques are being used to protect sensitive food components such as vitamins, flavors, or bioactive compounds against environmental factors like heat, light, or oxygen. These components are released in a controlled manner during storage or digestion, enhancing both stability and bioavailability [16]. Similarly, nanosensors embedded in packaging materials can detect gas emissions (like ethylene or ammonia) or microbial activity, allowing early identification of spoilage or contamination [17]. Such technologies contribute to reducing food waste and improving supply chain management. On the other hand, biomaterials derived from natural sources, such as chitosan, starch, gelatin, and alginate, are being used to create biodegradable films and edible packaging. These materials not only serve as protective barriers but may also be functionalized with agents that prevent microbial growth or oxidation. As a result, food stays fresh longer, and the environmental burden of packaging waste is significantly reduced [18].

The combined use of bionanotechnology and biomaterials in the food industry has led to numerous practical innovations. Antimicrobial and oxygen-resistant packaging: Nano-reinforced biopolymer films containing silver nanoparticles or zinc oxide offer strong antimicrobial properties and extended shelf life [19]. Active and intelligent packaging systems: These smart packages use nanosensors to provide visual or digital indications of temperature abuse, microbial growth, or freshness, helping consumers and distributors make timely decisions [20]. Nutritional enhancement: Nanocarriers are used to deliver micronutrients such as iron, calcium, or omega-3 fatty acids in fortified foods without affecting taste or texture [21]. Rapid pathogen detection: Nano-based diagnostic kits enable quick and highly sensitive detection of food borne pathogens like *E. coli* and *Salmonella*, supporting improved food safety [22]. The emerging of bionanotechnology and biomaterials has led to the development of intelligent food systems that can detect and respond to environmental changes such as microbial growth, pH shifts, and temperature fluctuations. These innovations are in line with global objectives focused on reducing food waste, enhancing food traceability, and supporting sustainable agriculture [23]. Furthermore, they respond to modern consumer expectations for clean-label, minimally processed, and traceable food products. However, despite their potential, there are still concerns surrounding consumer acceptance, health implications, and regulatory challenges. Issues such as nanoparticle toxicity, migration into food products, and the lack of harmonized global standards require further investigation and oversight [24]. Therefore, continuous interdisciplinary research is essential to ensure that these technologies are developed responsibly and applied safely. This paper aims to explore the current and emerging roles of bionanotechnology and biomaterials in the food industry. It examines innovative applications, evaluates their advantages and risks, and discusses future opportunities for building safer, more efficient, and sustainable food systems. Unlike prior reviews that individually highlighted biomaterials, bionanotechnology, biomedical applications, environmental remediation or food nanotechnology, this review provides an ample and updated integration of these interrelated fields. The review distinctly bridges applications across biomedical, environmental and food sectors, underscoring translational opportuni-

ties and common mechanisms. It also investigates both biomaterials and bionanotechnology within a unified framework rather than treating them as independent disciplines.

The review integrates emerging concepts including nano-bio hybrid interfaces, smart packing technologies and stimuli-responsive nanocarriers, which are often only briefly discussed in other reviews. It finally discusses safety, sustainability, regulatory challenges and future directions concurrently, facilitating a holistic understanding of current opportunities and limitations. Table 1 below gives a comparison between this and published papers

2.0. Bionanotechnology in Food Industries

Nanotechnology is anticipated to play a pivotal role in advancing research across numerous scientific and technological disciplines. One of the primary motivations behind its development is the growing challenge of further miniaturization in the microelectronics sector, which has begun to approach its physical and technical limitations [31]. Despite these origins, the potential applications of nanotechnology extend far beyond electronics. Notable examples include its use in energy-related innovations, such as the creation of nano structured catalysts, hydrogen storage systems, separation membranes, and nanoporous materials for catalytic support [31]. In addition, the field holds significant promise in medical and health technologies. These applications involve nanoscale sensors, advanced drug delivery systems, and engineered scaffolds for tissue regeneration [32]. Within this broader scope, bionanotechnology has emerged as a distinct subfield that integrates biological inspiration and systems into nanoscale engineering. This multi disciplinary area lies at the intersection of biology, physics, and engineering, focusing on the development and use of biomaterials, nanoscale devices, and biological techniques. These systems typically feature components ranging in size from molecules to several hundred nanometers [31].

2.1. Applications of Bionanotechnology

2.1.1. Medical and Health care Applications

Bionanotechnology has profoundly impacted biomedicine. Nanoparticles functionalized with ligands enable targeted drug delivery systems, reducing side effects and enhancing therapeutic efficacy [33]. For instance, gold and silica nanoparticles are used to transport anti-cancer drugs directly to tumor cells. Diagnostic techniques have also improved through the use of quantum dots and magnetic nanoparticles, which enhance imaging resolution in magnetic resonance imaging (MRI) and fluorescent tagging [34]. Moreover, biosensors made with nanostructured materials can detect disease biomarkers with ultra-high sensitivity, enabling early disease detection and real-time monitoring [35]. In tissue engineering, bionanotechnology is used to create nano fibrous scaffolds that mimic the extra cellular matrix, promoting cell adhesion, growth, and differentiation [36].

2.1.2. Agricultural and Food Applications:

In agriculture, bionanotechnology supports the development of nano-fertilizers and nanopesticides that offer controlled release and improved uptake, reducing waste and environmental contamination [37]. Nanosensors can detect pathogens and monitor soil conditions, facilitating precision agriculture and early disease control [38]. In the food industry, nano encapsulation techniques are applied to improve the bioavailability and stability of nutrients and food additives [39]. Smart packaging systems integrated with nanosensors can monitor

Table 1. Distinction between previous publications and the present review

Reference	Major Focus	Biomedical applications	Food applications	Environmental applications	Biosensors/ diagnostic	Sustainability and regulatory issues	Key Limitation
Farag (2023), [25] Recent Trends on Biomaterials for Tissue Regeneration Application	Biomaterials for tissue engineering and regeneration	✓	×	×	×	Limited	Restricted to regenerative medicine
Matic et. (2023), [26] nanostructured materials for drug delivery and tissue engineering applications	Nanomaterials in drug delivery and tissue engineering	✓	×	×	Limited	×	Underscores mainly therapeutic and regenerative applications
Salehi et al. (2023), [27] Smart Stimuli-responsive injectable Gels and Hydrogels	Stimuli-responsive biomaterials for drug delivery	✓	×	×	×	Limited	Limited focus on injectable hydrogels and therapeutic delivery
Jang et al. (2023), [28] Scaffold characteristic, fabrication methods, and biomaterials for bone and tissue engineering	Bone tissue engineering scaffolds	✓	×	×	×	×	Specialized emphasis on orthopedic applications
Ornaghi et al. (2023), [29] Polymers for Biomedical applications on hard and soft tissues and prosthetic limbs	Polymeric biomaterials in medicine	✓	×	×	×	Limited	Fails to cover food or environmental applications
Current review	Bionanotechnology and biomaterials across biomedical, food, environment-tal and diagnostic sectors	✓	✓	✓	✓	✓	Provides an integrated cross-sector viewpoint

freshness, detect microbial contamination, and signal spoilage, thereby enhancing food safety and shelf-life [40].

2.1.3. Environmental Applications:

Bionanotechnology provides solutions for water and air purification through the development of nanomaterials such as carbon nanotubes and silver nanoparticles that exhibit strong adsorption and antimicrobial properties [41]. These materials are used in filters and membranes to remove heavy metals, organic pollutants, and pathogens from environmental samples [42]. Bioremediation is also enhanced through the application of nanomaterials that can accelerate the breakdown of toxic compounds or immobilize contaminants in soil and ground water [43].

2.1.4. Energy Applications:

In the energy sector, bionanotechnology enables the development of more efficient solar cells by incorporating biomolecules such as photosynthetic proteins and chlorophyll analogs [44]. Bio-nanohybrid fuel cells convert chemical energy into electricity using enzymes and micro organisms supported on nanomaterials, offering sustainable and low-cost energy solutions [45].

2.2. Stimuli-responsive nanocarriers:

are "smart" drug delivery systems designed to react to internal (pH, enzymes, redox) or exterior (light, heat, magnetic fields) stimuli to release therapeutic drugs precisely at target areas (such as tumors). These nanostructures, which are frequently composed of lipids or polymers, enhance therapeutic efficacy, reduce adverse effects that are not intended, and enable regulated spatiotemporal drug release [46]. Important Features of Nanocarriers That Respond to Stimuli: Mechanism of Action: When stimulated by specific characteristics of the disease microenvironment or the application of external energy, these systems undergo structural changes (such as swelling, degradation, or contraction) while remaining stable in cir-

culation. Types of Stimuli: Endogenous and Internal respond to the pathogenic conditions, such as elevated glutathione (redox potential) in cells or low pH in malignancies.

2.3. Exogenous or external:

Initiated by stimuli applied by the user, such as ultrasonic, magnetic fields, heat, or light (UV or infrared). Structure: Usually made of hydrophilic outer shells and hydrophobic inner cores, they commonly use materials like polymers, liposomes, or micelles [47]. Principal Benefits: Targeted Delivery: Less harm to healthy tissue due to increased accumulation at the sick spot (such as the tumor microenvironment). Controlled Release: Enables exact drug release timing and dosage. Theranostics: Certain systems (such as contrast agents in ultrasonography) combine therapy and diagnostic imaging. Synthetic, non-living materials (such as nanoparticles, nanowires, and graphene) can directly interact with biological systems (such as cells, proteins, and DNA) at nanoscale interfaces known as nano-bio hybrid interfaces.

They enable targeted drug administration, accurate, high-sensitivity biological process monitoring, and the incorporation of artificial, improved functions into living things by facilitating signal transduction.

2.4. Key Aspects of Nano-Bio Interfaces:

Materials and Structure: These interactions frequently create structures like core-shell arrangements or nanowire-embedded sensors by combining organic biological components with inorganic, conducting, or semiconducting nanomaterials. **Functionality:** By bridging the gap between biological systems and inanimate technology, they enable "bioaugmentation," which gives organisms additional characteristics like improved conductivity, stress tolerance, or photosynthesis. **Uses:** Medicine: enhanced bioimaging, neural interfaces for brain-computer communication (BCIs), and targeted, stimuli-responsive medication administration. Energy and Environment: Solar-to-

chemical energy conversion and artificial photosynthesis using semiconductor-bacteria hybrids. Biosensing: The use of nano-biohybrids for extremely sensitive molecular interaction detection and analysis (e.g., DNA sequencing using nanopores) [48].

Through the combination of nanotechnology and artificial intelligence (AI), highly sensitive, intelligent, and self-governing devices that are capable of detecting physical, chemical, or biological stimuli at the nanoscale are known as AI-enabled nanosensors. These intelligent systems combine machine learning (ML) algorithms with nanomaterials including carbon nanotubes, graphene, and gold nanoparticles to detect analytes and perform real-time data analysis, interpretation, and action. Three primary layers make up the core components and functionality of AI-enabled nanosensors: Materials with high surface-to-volume ratios, such as graphene or gold nanoparticles, are used in the sensing layer (nanomaterials) to pick up on even the smallest changes in their surroundings. Electronics/IoT Data Processing Layer: Gathers signals, minimizes noise, and normalizes data [49].

2.5. AI-Driven Analytics Layer (The "Brain"):

Makes judgments, improves selectivity, and interprets data patterns using machine learning, deep learning, or neural networks. Important Benefits of Integrating AI Enhanced Sensitivity and Specificity: AI algorithms are able to overcome the limits of conventional, non-intelligent sensors by differentiating genuine, nuanced signals from background noise. AI-powered sensors have the ability to learn from operational data and adjust their performance in real-time, allowing for real-time analysis and self-calibration. Pattern Recognition: Rather than depending on a single marker, AI recognizes distinct, multi-analyte "fingerprints" for disease in complicated contexts (such as human breath or blood). Predictive Capabilities: AI is able to predict illness development, pollution surges, and maintenance requirements [50].

2.6. Major Applications

Healthcare and Diagnostics: Wearable sensors (smartwatches, patches) or "electronic noses" (breath analyzers) are used for non-invasive, early disease detection (e.g., cancer, COVID-19, diabetes).

2.7. Environmental Monitoring:

Used for autonomous, real-time monitoring of air and water quality, contamination detection, and purification process control. By improving their autonomy, nanorobots can deliver drugs more precisely by navigating intricate biological systems and delivering payloads to precise tumor locations [51].

2.8. Agriculture:

Used to monitor volatile organic compounds (VOCs) in order to identify nematodes, plant diseases, or nutrient deficits early.

Future Directions and Challenges

The combination of AI with nanosensors is still in its infancy, despite its potential. Future research will concentrate on Edge Computing, which processes data directly on the chip, and Quantum Machine Learning (QML), which can handle small, high-dimensional datasets. Important difficulties include: Data Scarcity: To train AI models, vast, high-quality datasets are required. Model Interpretability: For clinical trust, more explainable AI (XAI) is needed due to the "black box" nature of some AI models. Safety and Biocompatibility: Making sure nanoparticles don't damage biological systems over time. Comparism between nano-enabled and conventional systems using performance metrics is given in Table 2

3.0. Bionanotechnology in the Food Industry

The integration of bionanotechnology into the food industry has opened new frontiers in food processing, preservation, packaging, and safety. This interdisciplinary innovation combines nanotechnology with biological systems to solve long-standing challenges related to food spoilage, contamination, nutrient delivery, and shelf-life. Through the manipulation of matter at the molecular and atomic levels, bionanotechnology offers enhanced control over food quality, safety, and functionality [52]. As global food demand continues to increase, the application of bionanotechnology becomes sential to ensuring food sustainability, traceability, and nutritional value. Figure 2 following will illustrate Nanotechnology for the food industry.

3.1. Applications of Bionanotechnology in Food Systems

3.1.2. Food Safety and Quality Monitoring:

One of the most promising applications of bionanotechnology in the food industry is in safety monitoring. Nanosensors and biosensors are being developed to detect microbial contamination, spoilage, and allergens in real time [40]. These sensors rely on nanostructured materials, such as carbon nanotubes, gold nanoparticles, and quantum dots, which are functionalized with biomolecules (e.g., antibodies, enzymes, or aptamers) that recognize specific targets. For example, silver nanoparticles with antimicrobial properties are used in biosensing platforms to detect *E. coli*, *Salmonella*, and *Listeria* in food samples [40]. These nanosensors are not only highly sensitive and rapid but can be integrated into packaging systems for continuous monitoring during storage and transportation. Ensuring food safety and maintaining quality are major priorities in the global food industry, as contamination, adulteration, and spoilage continue to pose significant health and economic challenges. Conventional methods for monitoring such issues are often labor-intensive, time-consuming, and costly. In contrast, bionanotechnology provides rapid, reliable, and highly sensitive solutions by combining nanoscale materials with biological recognition systems to create innovative monitoring platforms [40]. Food borne pathogens such as *Escherichia coli*, *Salmonel*

Table 2. COMPARISM BETWEEN NANO-ENABLED AND CONVENTIONAL SYSTEMS USING PERFORMANCE METRICS (SENSITIVITY, MIGRATION RISK, SCALABILITY)

METRIC	NANO-ENABLED SYSTEMS	CONVENTIONAL SYSTEMS
Sensitivity	Extremely High: Superior, especially for sensors/detectors, due to higher surface-to-volume ratio	Moderate to Low: Limited by surface-governed phenomena and slower reaction times
Migration Risk	High Concern: Small particle size increases risk of leaching into consumables (food/water)	Low: Particles are typically in micrometer or larger ranges, minimizing migration
Scalability	Moderate: High-cost production and batch-to-batch variability	High: Mature, cost-effective, and easy to manufacture at scale
Performance	High Efficiency: Enhanced reactivity, faster kinetics, and lower energy usage	Moderate: Higher energy consumption and lower contaminant removal



Figure 2. Overview of Nanotechnology for food industry [53].

la spp., and *Listeria monocytogenes* remain primary causes of food borne illnesses worldwide. Bionanotechnology facilitates the development of nanobiosensors, where nanomaterials like gold nanoparticles, carbon nanotubes, or quantum dots enhance signal transduction for pathogen detection at very low concentrations. These biosensors enable real-time monitoring of food during processing and distribution, thereby reducing outbreak risks [54]. Another major safety concern is contamination by mycotoxins, pesticide residues, and allergenic proteins. Nanoscale biosensors, particularly aptamer-based platforms and nanostructured electrodes, offer high specificity and sensitivity for these compounds. For instance, gold nanoparticle-based colorimetric sensors allow visible detection of allergens, providing quick and user-friendly on-site screening methods without requiring specialized laboratories [55]. Monitoring of Food Freshness and Spoilage: Spoilage detection is critical to ensure product quality and consumer safety. Smart packaging systems integrated with nanosensors can detect chemical markers such as pH, carbon dioxide, ammonia, and volatile organic compounds (VOCs), which indicate microbial activity. These nanocomposites often display measurable color changes when food deterioration occurs, serving as a direct freshness indicator to consumers and retailers [56]. Real-Time Quality Assessment: Beyond detecting hazards, bionanotechnology supports authentication and nutritional quality assessment. Nanosensors are capable of detecting adulteration in high-value commodities like milk, honey, and olive oil. Similarly, spectroscopic and nanoscale imaging tools can monitor structural and compositional changes in food matrices, ensuring preservation of nutritional and sensory attributes [57]. Integration with Digital and IoT Systems: Recent advances emphasize the integration of nanosensors with wireless communication and Internet of Things (IoT) platforms. Sensors embedded in packaging materials or storage systems can transmit real-time data on temperature, humidity, and microbial contamination. This digital traceability enhances supply chain transparency, regulatory compliance, and consumer confidence [58]. Bionanotechnology enhances food safety and quality monitoring by providing rapid, sensitive, and cost-effective tools. From pathogen detection to freshness evaluation and IoT-enabled traceability, these applications reduce foodborne risks and support sustainable food manage-

ment [54].

3.1.3. Intelligent and Active Food Packaging:

Bionanotechnology plays a pivotal role in the development of active and intelligent packaging systems that respond to environmental changes or detect spoilage. Intelligent packaging incorporates nanosensors that can monitor temperature, humidity, and gas composition, offering visual indicators of freshness and spoilage [59]. Active packaging, on the other hand, contains antimicrobial or oxygen-scavenging nanoparticles that interact with the food or its environment to prolong shelflife. For example, zinc oxide and silver nanoparticles are used in packaging films to inhibit the growth of bacteria and fungi [60]. Such packaging systems not only reduce food waste but also eliminate the need for chemical preservatives. The use of bionanotechnology has significantly advanced food packaging by creating intelligent and active systems that go beyond the traditional role of serving as a passive protective barrier. Instead, these novel packaging strategies are designed to interact with food and its environment to enhance quality, extend shelf life, and improve safety [61]. In the case of active packaging, nanomaterials such as antimicrobial nanoparticles, oxygen absorbers, and moisture controllers are incorporated into packaging matrices to maintain food integrity. For instance, silver nanoparticles and chitosan-based nanocomposites have demonstrated strong antimicrobial properties, helping to reduce microbial contamination during storage and distribution [62]. Similarly, the addition of nanoclays and titanium dioxide (TiO₂) nanostructures has been shown to enhance gas and ultraviolet (UV) barrier properties, which play an essential role in protecting food against oxidation and spoilage [63]. Intelligent packaging, on the other hand, uses nanosensors and biochemical indicators that can provide real-time information about food conditions. For example, nanosensors capable of detecting changes in pH or volatile compounds can produce visible color changes, thereby signaling the degree of freshness of packaged products [40]. In addition, nucleic acid and protein-based nanosensors are being designed to detect pathogenic organisms such as *Escherichia coli* and *Salmonella*, allowing contamination to be identified directly within the packaging without requiring laboratory analysis [54]. The synergy between in-

telligent and active packaging not only enhances food preservation but also promotes transparency and reduces waste. For consumers, such technologies ensure safer food consumption, while industries benefit from improved monitoring and extended shelf life of products. Furthermore, the adoption of biodegradable nanocomposites in packaging design reflects an environmentally conscious effort, reducing plastic-related waste and supporting sustainability initiatives [64].

3.2. Traceability and Authentication

Nanobarcodes and DNA-based nanoparticle tags are being explored for their potential in food traceability and authentication. These nanostructures can carry encrypted information about the origin, production, and transportation of food products, allowing real-time verification and anti-counterfeiting measures [65]. This is particularly important in high-value products such as organic, halal, or geographically protected food items, where authenticity is a key concern. Bionanotechnology is increasingly applied in food systems to improve traceability and authentication, two crucial aspects for ensuring safety and consumer trust. Traceability involves tracking food products throughout the supply chain, while authentication verifies the originality and prevents fraud or mislabeling. Traditional methods such as barcodes and paperwork are often limited, but nanoscale innovations are addressing these gaps. [66]. For example, nanobarcodes, quantum dots, and nanoparticle-based inks have been designed to store encrypted data in packaging and labeling systems, enabling accurate product tracking from production to consumption [67]. Similarly, nanosensors incorporated into packaging materials can monitor environmental changes, contamination, or tampering in real time, providing reliable supply chain monitoring [40]. Authentication is also significantly strengthened by bionanotechnology. Advanced techniques like DNA barcoding, nano-biosensors, and surface-enhanced Raman scattering (SERS) tags allow differentiation between authentic and counterfeit food items [68]. DNA-encoded nanoparticles, for instance, serve as molecular fingerprints that are extremely difficult to forge, thereby improving the detection of adulteration and ensuring product authenticity [69]. Furthermore, the integration of bionanotechnology with digital platforms such as blockchain and the Internet of Things (IoT) is enhancing transparency and security in food systems. This combination allows nanoscale traceability tools to work seamlessly with digital ledgers, providing tamper-proof records and improving consumer confidence [70].

3.3. Benefits of Bionanotechnology in Food Industry: The adoption of bionanotechnology in the food sector provides several advantages:

3.3.1. Improved Food Safety:

Rapid detection of pathogens and contaminants reduces the risk of food borne illnesses. Improved food safety is one of the major advantages of applying bionanotechnology in the food sector. Through the use of nanobiotechnology, rapid and highly sensitive systems have been developed to detect harmful contaminants such as toxins, allergens, pesticide residues, and foodborne pathogens at very low levels, thereby preventing outbreaks before they become widespread [71]. Smart packaging technologies enhanced with nanomaterials further contribute to safety by monitoring real-time changes in food products, such as variations in pH or the release of spoilage gases, which can alert consumers and retailers about potential hazards [72]. In addition, antimicrobial nanoparticles including silver, zinc

oxide, and chitosan-based nanostructures have been incorporated into packaging films and edible coatings, helping to suppress microbial growth and extend product shelf life [73]. Collectively, these innovations reduce foodborne risks, improve quality assurance, and strengthen consumer confidence in food systems.

3.3.2. Enhanced Nutritional Value:

Bionanotechnology significantly contributes to the food industry by improving the nutritional value of food products. Through approaches such as nanoencapsulation and nanoscale delivery systems, vital nutrients including vitamins, minerals, antioxidants, and bioactive compounds are made more stable and bioavailable [74]. For example, delicate nutrients like vitamin D, omega-3 fatty acids, and probiotics, which often degrade during storage or processing, can be protected using nanocarriers such as liposomes, nanoemulsions, and polymeric nanoparticles, ensuring controlled release during digestion [75]. Additionally, bionanotechnology enhances food fortification by increasing the solubility and absorption of compounds with low water solubility, such as carotenoids and curcumin, when delivered through nanostructured carriers [76]. Functional foods developed using these systems therefore provide more effective nutritional and health benefits compared to conventional supplementation methods. Moreover, smart nanocarriers allow for targeted nutrient delivery in the gastrointestinal tract, thereby reducing nutrient loss and maximizing physiological benefits [77].

3.3.3. Extended Shelf-Life:

Active packaging inhibits spoilage, reducing food loss. Bionanotechnology plays a significant role in the food industry by contributing to the prolongation of shelf life of food products. The application of nanostructured materials and bio-based nanocomposites helps preserve foods for longer durations while retaining their nutritional and sensory qualities. For example, the integration of nanoparticles such as silver, zinc oxide, and chitosan into packaging systems provides antimicrobial and antioxidant functions that effectively slow down microbial contamination and oxidative spoilage [61]. In addition, the use of nanosensors in smart packaging enables real-time detection of early spoilage signals and the controlled release of active compounds to delay deterioration [78]. By extending freshness and stability, these innovations not only minimize food loss during storage and distribution but also promote sustainability and enhance global food availability [79].

3.3.4. Efficient Processing:

Nanostructured enzymes and catalysts optimize food manufacturing. Bionanotechnology has greatly enhanced the efficiency of food processing by introducing nanoscale innovations that reduce time, energy, and resource consumption. One major contribution is the use of nanostructured enzymes, which exhibit higher catalytic activity and stability, thereby accelerating biochemical reactions and improving product yield [80]. These nanobiocatalysts enable essential processes such as fermentation, emulsification, and hydrolysis to occur under milder conditions, which not only lowers energy requirements but also preserves heat-sensitive nutrients in foods [81]. Another advantage of bionanotechnology lies in improving extraction and incorporation of bioactive compounds. Nanoemulsions and nanocarriers enhance the solubility and bioavailability of hydrophobic ingredients, allowing their rapid integration into food systems while minimizing the use of solvents and additives [82]. In addition, the integration of nanosensors into production lines allows real-time

monitoring of parameters like pH, temperature, and microbial growth, which reduces processing errors and ensures consistent product quality [56].

3.3.5. Better Consumer Information:

Smart packaging offers real-time data on food freshness. Bionanotechnology is transforming the way consumers' access and interpret food-related information by integrating nanosensors and smart packaging into the food supply chain. These nanosensors, often made from nanomaterials such as carbon nanotubes, metal nanoparticles, and quantum dots, are capable of detecting microbial contamination, chemical residues, and spoilage markers at very low concentrations, providing real-time feedback on food safety and freshness [83]. Smart packaging systems equipped with these nanosensors can display simple signals such as color changes or scannable QR codes that inform consumers about the quality and storage conditions of a product, reducing uncertainty and minimizing food waste [84]. Beyond packaging, nanosensor data can also be integrated with digital platforms, such as blockchain or IoT-based traceability systems, giving consumers access to detailed information about the origin, processing, and distribution of food items [58]. This improved transparency not only helps consumers make healthier and more informed purchasing decisions but also strengthens trust in food brands and regulatory frameworks. In addition, studies show that consumers are increasingly willing to pay a premium for products with verifiable safety and origin information, which makes nano-enabled traceability and smart packaging a competitive advantage for food producers [85]. By providing accurate, accessible, and interactive information, bionanotechnology serves as a bridge between producers and consumers, ensuring authenticity, safety, and quality across the food value chain [31].

4.0. Biomaterials in Food Industries

Biomaterials are natural or synthetic materials that are engineered to interact with biological systems for medical, industrial, or environmental applications. Originally developed for medical im-

plants and prosthetics, the scope of biomaterials has since expanded into sectors such as tissue engineering, drug delivery, food packaging, biosensors, and bioelectronics [86]. A fundamental characteristic of biomaterials is their biocompatibility, meaning they must function in contact with living tissues without causing adverse actions such as inflammation, toxicity, or immune rejection. Figure 3 below illustrate the types of Biomaterials. They are further regarded as substances (other than a drug) or combination of substances, synthetic or natural in origin, which can be used for a period of time, as a whole or as part of a system, which treats, augments, or replaces any tissue, organ, or function of the body" [87]. Some of the advantages of biomaterials are Biocompatibility, Versatility, Sustainability, and Functionalization.

4.1. Classification of Biomaterials:

Biomaterials are classified in the following categories (Fig 3) as discussed below

4.1.1. Natural Biomaterials :

Derived from living organisms, such as collagen, gelatin, alginate, chitosan, silkfibroin, cellulose, and hyaluronic acid [88].

4.1.2. Synthetic Biomaterials:

Engineered polymers (e.g.,PLA,PCL,PEG), metals(e.g.,titanium, stainlesssteel), ceramics(e.g.,hydroxyapatite, alumina), and composites [89].

4.1.3. Hybrid Biomaterials:

Combine natural and synthetic components to achieve specific mechanical, chemical, or biological properties [90].

4.2. Applications of Biomaterials

4.2.1. Biomedical and Clinical Applications:

Biomaterials have gained prominence in modern healthcare due

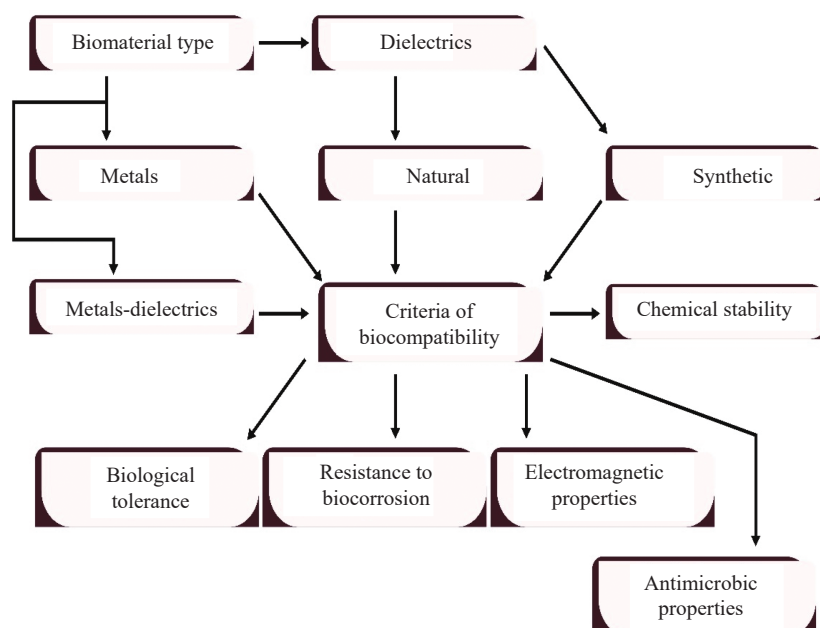


Figure 3. Classification of Biomaterials [91].

to their ability to interact safely with biological systems, making them vital in both biomedical and clinical practices [92]. In orthopedics, they are widely employed in bone grafting, joint replacements, and fixation devices, where metals, ceramics, and polymers provide mechanical strength while supporting tissue healing [93]. Similarly, dental applications such as implants, restorative fillings, and scaffolds for gum regeneration rely on hydroxyapatite and polymeric composites because of their bioactivity and durability [94]. In cardiovascular treatment, biomaterials contribute to the development of artificial heart valves, vascular grafts, and drug-eluting stents that minimize clot formation and improve patient recovery [95]. They are also important in wound care and tissue engineering, where natural polymers like collagen, chitosan, and alginate are used in dressings and skin substitutes to accelerate healing and encourage new tissue growth [96]. Furthermore, biomaterials enhance drug delivery through nanoparticles, hydrogels, and micelles that allow targeted and controlled release, thereby reducing adverse effects while improving therapeutic outcomes [92]. In ophthalmology, they are applied in intraocular lenses, corneal scaffolds, and contact lenses that support vision correction and sustained drug administration [97]. Additionally, advances in neural engineering have introduced conductive polymers and nanostructures to aid nerve regeneration and interface with brain signals. Overall, the integration of biomaterials into clinical medicine has improved patient care by enabling safer, more efficient, and personalized treatment approaches.

4.2.2. Tissue engineering:

Tissue engineering is a key biomedical application of biomaterials, as it integrates concepts from medicine, biology, and engineering to restore or replace damaged tissues [98]. In this field, biomaterials act as scaffolds that provide a supportive framework for cell growth, attachment, and differentiation, which are vital for the regeneration of functional tissues. Both natural and synthetic biomaterials are widely utilized, depending on the clinical need. Natural materials such as collagen, alginate, and chitosan are particularly valued because of their inherent biocompatibility and ability to enhance cellular adhesion [90]. Conversely, synthetic polymers like polylactic acid (PLA) and polycaprolactone (PCL) are preferred when controlled mechanical strength and degradation rates are required for customized tissue substitutes [99]. Recent advancements such as nanotechnology and 3D bioprinting have strengthened the role of biomaterials in this discipline. These technologies enable the creation of scaffolds that closely resemble the extracellular matrix (ECM), thereby improving nutrient diffusion and promoting vascularization, which are crucial for sustaining engineered tissues [100]. Practical applications of tissue engineering include artificial skin for burn patients, cartilage regeneration for orthopedic treatments, vascular grafts for cardiovascular repair, and experimental progress toward organ regeneration such as liver and kidney tissues [101]. These examples emphasize how biomaterials play a central role in bridging scientific innovation with clinical solutions in regenerative medicine [102].

4.2.3. Implants and prosthetics:

Biomaterials are widely applied in the production of implants and prosthetic devices, as they provide structural and functional solutions for damaged or missing body parts. Implants are medical devices placed inside the body to support or replace biological structures, such as joint replacements, dental fixtures, and cardiovascular stents, while prosthetics are external devices designed to substitute

lost body parts, such as artificial limbs and facial prostheses [103]. The choice of biomaterials for implants is highly influenced by their mechanical strength, durability, and biocompatibility. For instance, orthopedic implants like hip and knee replacements often employ titanium and cobalt chromium alloys because they combine excellent load-bearing ability with resistance to corrosion, ensuring long-term stability within the body [104]. In addition, polymers such as polyethylene and polymethylmethacrylate (PMMA) are frequently used in joint prostheses since they provide flexibility and reduce wear at articulation sites [105]. In the case of prosthetics, biomaterials are expected not only to withstand mechanical stress but also to mimic the appearance and texture of natural tissues. For example, silicone elastomers are commonly employed in maxillofacial prosthetics because they are adaptable and capable of recreating lifelike aesthetics [106]. Recent developments have further integrated advanced materials with sensors and actuators in prosthetic limbs, allowing for improved mobility, sensitivity, and patient control [107]. Moreover, surface engineering of implants using nanostructures and bioactive coatings has significantly enhanced their performance. These modifications encourage better bonding with bone tissue (osseointegration) and minimize infection risks, thereby improving the long-term success of implanted devices [108]. Overall, the use of biomaterials in implants and prosthetics goes beyond structural replacement, contributing to both functional restoration and an improved quality of life for patients.

4.2.5. Drug delivery systems:

The application of biomaterials in drug delivery systems has significantly transformed therapeutic practices by enabling controlled, sustained, and targeted release of pharmaceuticals. Unlike traditional delivery routes that often cause fluctuations in drug concentration, biomaterial-based carriers provide steady and localized release, thereby enhancing efficacy and minimizing adverse reactions [109]. Various biomaterials, including polymers, hydrogels, liposomes, micelles, and nanoparticles, are designed for this purpose. For instance, biodegradable polymers such as polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA) degrade gradually in the body, ensuring predictable and sustained drug availability. In addition, lipid-based systems such as liposomes enhance drug solubility and stability, making them suitable for compounds with poor water solubility [92]. A major advancement involves targeted delivery, where biomaterials are engineered to recognize specific tissues or cellular receptors. Functionalized nanoparticles, for example, can be directed to accumulate in tumor regions, thereby improving the efficiency of anticancer drugs while reducing damage to healthy tissues [110]. Moreover, the development of stimuli-responsive biomaterials, such as pH-sensitive or thermo-responsive hydrogels, allows for site-specific drug release triggered by environmental changes, thus providing more precise control over therapy [111]. In summary, the integration of biomaterials into drug delivery systems has improved pharmacological outcomes through controlled release, enhanced bioavailability, and reduced systemic toxicity, establishing them as a cornerstone in the treatment of chronic diseases, infections, and cancer [92].

4.2.6. Wound dressings:

Biomaterials play a vital role in the development of wound dressings, as they not only provide coverage and protection but also actively support the healing process. Unlike traditional dressings, modern biomaterial-based systems are designed to maintain an optimal microenvironment, prevent microbial invasion, and promote tis-

sue regeneration [112]. A wide range of natural and synthetic biomaterials are utilized for wound care. Natural polymers such as collagen, chitosan, alginate, and hyaluronic acid are widely applied due to their high biocompatibility and ability to mimic the extracellular matrix (ECM), which aids cell growth and repair [90]. For example, chitosan possesses antimicrobial activity and promotes blood clotting, while alginate dressings are effective in managing wounds with heavy exudates because of their excellent moisture-retaining properties [113]. On the other hand, synthetic polymers such as polyurethane, polyethylene glycol, and polyvinyl alcohol offer flexibility, durability, and controlled degradation rates, making them suitable for advanced wound care applications [114]. Furthermore, bioactive wound dressings have emerged, incorporating components like nanoparticles, growth factors, and antimicrobial agents to accelerate healing. These dressings not only act as protective barriers but also actively deliver therapeutic agents, thereby reducing infection risks and enhancing tissue repair [115]. For instance, nanostructured biomaterials improve oxygen diffusion at the wound site and provide targeted drug delivery. More recently, smart wound dressings have been developed, which can respond to changes in wound conditions such as pH, moisture, or temperature, releasing drugs only when required [116]. In summary, biomaterials in wound dressings represent a shift from passive wound coverage to active healing facilitation. Their unique features including biocompatibility, antimicrobial potential, biodegradability, and moisture control make them indispensable in modern wound management and therapeutic strategies [117].

4.3. Biosensors and Diagnostics

A biosensor is a specialized analytical tool that merges a biological recognition system, such as enzymes, antibodies, or nucleic acids, with a physical transducer to generate measurable signals in response to the detection of target substances [118]. This integration allows for rapid and precise identification of analytes across medical, industrial, and environmental fields. Structurally, biosensors comprise three essential parts: a bioreceptor that specifically interacts with the analyte, a transducer that translates the biological event into an electrical, optical, or thermal signal, and a signal processor or display that interprets and presents the result in a readable form [119]. Biosensors can be categorized into various types depending on their transduction mechanism. Electrochemical biosensors measure changes in current or potential, optical biosensors exploit properties like fluorescence or surface plasmon resonance, thermal biosensors detect heat changes during biochemical reactions, while piezoelectric biosensors sense variations in mass or acoustic vibrations [120]. In terms of diagnostics, biosensors are becoming indispensable for detecting diseases, pathogens, and physiological conditions. Their utility spans medical fields, where they are used for glucose monitoring in diabetes and rapid detection of infectious diseases such as HIV and COVID-19 [121]. In the food industry, biosensors help in identifying microbial contaminants like *Salmonella* and *Escherichia coli*, ensuring food safety [122]. They are also crucial in environmental monitoring, detecting heavy metals, pesticides, and other pollutants, while in biodefense, they provide rapid screening of potential biological threats [123]. The benefits of biosensors in diagnostics include their high sensitivity, specificity, and ability to provide rapid results compared to conventional laboratory tests. Moreover, they are cost-effective, user-friendly, and increasingly portable [124]. Despite these advantages, challenges such as the instability of biological components, limited reusability, and the need for regulatory standardiza-

tion remain obstacles to their widespread adoption [125].

4.5. Biomaterials in Food Industries

Biomaterials are increasingly gaining attention in the food industry due to their potential to address challenges related to sustainability, safety, shelf-life, and consumer health. Derived from natural or synthetic sources, biomaterials in food systems are used for packaging, processing aids, coatings, sensors, and delivery of nutrients or bioactives. Their biocompatibility, biodegradability, and ability to interact with food matrices without adverse effects make them ideal for developing environmentally friendly and health-conscious food solutions [126]. In the context of food industries, biomaterials refer to materials that are safe, edible or food-contact compliant, and are derived from biological sources or engineered to mimic natural systems. These materials can be classified into: Natural biopolymer (e.g., starch, cellulose, alginate, gelatin, chitosan, whey protein [90]), Synthetic biodegradable polymer (e.g., polylactic acid (PLA), polyhydroxyalkanoates (PHAs) [127]), Composite biomaterials, Combinations of natural and synthetic materials for improved performance [128].

4.6. Applications of Biomaterials in the Food Industry

4.6.1. Biodegradable Food Packaging:

One of the most prominent uses of biomaterials in the food sector is biodegradable packaging, which offers an alternative to petroleum-based plastics. Films and coatings made from starch, chitosan, and PLA have shown effectiveness in preserving food quality by acting as barriers to moisture, oxygen, and microbial invasion. For example, chitosan-based films exhibit antimicrobial properties that help in extending the shelf life of fruits, vegetables, and meat [129].

4.6.2. Edible Coatings and Films:

Edible coatings, derived from proteins (e.g., casein, whey), polysaccharides (e.g., alginate, pectin), or lipids, are applied directly on food surfaces to reduce dehydration, oxidation, and microbial growth [130]. These coatings are widely used on fresh produce, cheese, confectionery, and bakery products. Biomaterial-based coatings can also be enriched with natural antioxidants and antimicrobials to enhance food safety.

4.6.3. Encapsulation of Nutrients and Bioactives:

Biomaterials enable micro- and nanoencapsulation of sensitive compounds such as vitamins, minerals, omega-3 fatty acids, polyphenols, and probiotics. This technology protects bioactives from degradation during processing and digestion, improves their solubility, and allows controlled release [131]. For example, alginate and whey protein are commonly used as encapsulating agents for probiotics in dairy and functional beverages.

4.6.4. Smart and Active Packaging Systems:

Functional biomaterials are also used in smart packaging systems that can respond to environmental conditions or detect changes in food quality. These include biosensors embedded in packaging films to detect spoilage gases (R), pH changes, or microbial activity [132]. Biomaterials can serve as carriers for indicators or antimicrobial agents, transforming the packaging from passive to active systems.

4.6.5. Food Processing Aids:

Biomaterials such as enzymes immobilized on biopolymers are

used to improve processing efficiency in dairy, baking, and brewing industries. Biodegradable polymers are also used in food contact materials like trays, films, and containers that comply with food safety regulations [133].

4.7. Advantages of Biomaterials in Food Applications

4.7.1. Biodegradability:

One of the major benefits of biomaterials in food-related applications is their biodegradability, which distinguishes them from conventional petroleum-based plastics. Unlike synthetic polymers that persist in the environment for centuries, biomaterials obtained from renewable resources such as polysaccharides, proteins, and biopolymers can undergo natural decomposition into harmless end-products like carbon dioxide, water, and biomass [132]. A key advantage is their contribution to reducing environmental pollution. Plastic packaging is one of the main contributors to solid waste accumulation and microplastic contamination in soil and marine ecosystems. In contrast, biodegradable biomaterials significantly lower this burden, as they degrade within relatively short periods under suitable conditions [134]. Another important aspect is sustainability. Since most biodegradable biomaterials are derived from agricultural products or by-products of food processing, they support the principles of a circular economy by minimizing waste and reducing dependence on fossil fuel-based raw materials [135]. Additionally, many biodegradable biomaterials are compostable, allowing safe disposal and even adding value to the ecosystem. When composted, these materials can return nutrients to the soil, thereby improving soil health and supporting agricultural productivity. From a socio-economic perspective, consumer acceptance of biodegradable packaging is also growing. Environmentally conscious consumers increasingly prefer eco-friendly products, and companies adopting biodegradable biomaterials often enjoy enhanced brand reputation and competitiveness [136]. Furthermore, the adoption of these materials helps industries comply with stringent regulations being implemented globally to phase out single-use plastics [137]. Finally, the carbon footprint reduction associated with biodegradable biomaterials is significant. Because they are largely plant-based, their production often results in lower greenhouse gas emissions compared to petroleum-derived plastics, with some raw materials even acting as carbon sinks during cultivation [135]. In summary, the biodegradability of biomaterials not only addresses the pressing problem of plastic pollution but also aligns with global sustainability goals, making them highly suitable for food applications.

4.7.2. Edibility and Safety:

A significant advantage of biomaterials in food applications lies in their edibility and safety. Unlike petroleum-based plastics, many biomaterials are produced from natural polymers such as starch, cellulose, proteins, and chitosan, which are inherently non-toxic and in some cases consumable [138]. This characteristic reduces risks of harmful chemical migration into food and builds consumer confidence in packaging solutions. The edibility aspect of biomaterials is especially relevant in the development of edible coatings and films, which can be consumed together with the food product. These coatings not only act as barriers against oxygen, moisture, and microbial activity but also reduce the reliance on synthetic packaging materials, thereby promoting sustainability [139]. For example, coatings made from polysaccharides and proteins help maintain food freshness while being entirely safe for ingestion. From a safety perspec-

tive, biomaterials are recognized for their biocompatibility and biodegradability, making them less likely to pose toxicological risks compared to synthetic packaging. International regulatory bodies such as the FDA and EFSA encourage the use of such food-grade materials, since they comply more readily with health and safety standards [140]. Additionally, some edible biomaterials can be enhanced with antimicrobial compounds or nutraceuticals, improving both food preservation and consumer well-being [140]. Thus, the combined benefits of edibility and safety position biomaterials as a superior alternative to conventional packaging in food applications, offering both consumer protection and environmental sustainability.

4.7.3. Renewable Source:

An important advantage of biomaterials in food applications is that they are derived from renewable resources. Unlike synthetic materials obtained from petroleum, biomaterials are sourced from plants, microorganisms, and agricultural by-products, which can be replenished naturally [141]. This renewable origin reduces dependency on finite fossil reserves and supports long-term material availability. The renewable property of biomaterials also enhances sustainability by enabling a circular use of resources. Agricultural residues and food waste, for instance, can be converted into raw materials for biopolymers used in packaging and edible coatings [142]. This process not only minimizes waste but also aligns with eco-friendly production practices. Moreover, using renewable feedstocks helps to lower carbon emissions and contributes to reducing the negative environmental impact of the food industry [143]. Biopolymers such as starch, cellulose, and polylactic acid (PLA) are good examples of renewable alternatives that replace synthetic plastics in packaging while maintaining functionality. Overall, the renewable source of biomaterials ensures continuous supply, environmental sustainability, and a shift towards greener food systems [144].

4.7.4. Antimicrobial and Antioxidant Properties:

One major advantage of biomaterials in food systems is their ability to provide antimicrobial protection, which helps suppress the growth of foodborne pathogens and spoilage microorganisms. This function is particularly valuable for perishable products such as meat, dairy, and fresh produce, where microbial activity can rapidly reduce shelf life [133]. By inhibiting microbial proliferation, biomaterials act as a natural barrier to contamination and foodborne illness. In addition to antimicrobial effects, biomaterials often display antioxidant activity, which is important in preventing oxidative deterioration of food. Lipid oxidation, for instance, is a leading cause of rancidity, discoloration, and nutrient degradation in packaged products. Incorporating natural antioxidants such as phenolic compounds, chitosan, or extracts from plants into biomaterial matrices helps delay oxidation and maintain the nutritional and sensory quality of food [145]. The combination of antimicrobial and antioxidant functions not only prolongs the freshness of food but also reduces dependence on synthetic preservatives, meeting consumer demand for clean-label and sustainable food options. Such biomaterials contribute to the development of active and intelligent packaging systems that improve safety while supporting environmental goals [146].

4.7.5. Improved Nutrient Delivery:

Biomaterials significantly contribute to improving nutrient delivery in food systems by enhancing the stability, solubility, and absorption of essential compounds. Through advanced techniques such as nano-encapsulation and polymer-based carriers, sensitive nutrients

like vitamins, probiotics, and omega-3 fatty acids can be shielded from degradation during processing and digestion, thereby improving their bioavailability [146]. For instance, the use of biopolymers such as alginate and chitosan in encapsulation allows for controlled and targeted release of nutrients within the gastrointestinal tract, ensuring maximum health benefits. Moreover, nanocarrier-based systems not only protect bioactive compounds from oxidation but also facilitate efficient delivery to specific sites in the body, thereby optimizing nutrient utilization [77]. Consequently, the incorporation of biomaterials into food applications provides a promising strategy for enhancing nutritional value and promoting consumer health [141].

5.0. Properties of Biomaterials:

The effectiveness of a biomaterial is determined by the following;

5.1.1. Biocompatibility:

Biocompatibility refers to the capacity of a material to function appropriately in a biological system without producing harmful effects at either the local or systemic level. In simple terms, it describes how safely a biomaterial, device, or coating interacts with living tissues while ensuring the desired therapeutic or technological outcome is achieved [147]. This concept is central to the development of medical implants, drug delivery systems, biosensors, tissue scaffolds, and even food-contact materials [148]. Factors Affecting Biocompatibility: Chemical Composition; The presence of toxic substances or degradation by-products can trigger inflammatory or cytotoxic reactions. For instance, the release of metal ions from alloys may lead to adverse effects [13]. Surface Properties; Characteristics such as hydrophilicity, roughness, and surface chemistry influence protein adsorption and cell adhesion [149]. Nano-patterned surfaces, for example, can enhance tissue integration compared to flat surfaces. Mechanical Properties; The mechanical strength and elasticity of biomaterials must align with the host tissue. Orthopedic implants, for instance, require high stiffness, while soft tissue scaffolds must be flexible [150]. Degradation and Stability; Biodegradable materials should degrade at a predictable rate into non-toxic by-products, whereas permanent implants must remain stable over time [151]. Sterilization Compatibility; Materials should tolerate sterilization techniques such as heat, radiation, or chemical treatment without compromising structure or function [152].

5.1.2. Mechanical Strength:

Resistance to stress and deformation. Mechanical strength is one of the most critical attributes of biomaterials, describing their ability to resist forces such as tension, compression, bending, or torsion without undergoing fracture or irreversible deformation. This property is vital in biomedical applications since implants, prosthetics, and scaffolds are often exposed to complex physiological loads during normal bodily functions [153]. There are different forms of mechanical strength that are significant in biomaterial science. Tensile strength refers to the maximum pulling force a material can withstand before failure, making it essential for applications such as sutures, tendon, and ligament replacements. Compressive strength, on the other hand, relates to the ability to resist forces that press the material together, which is particularly important for bone grafts and dental restorations. Flexural strength reflects resistance to bending forces, a property crucial for dental bridges and orthopedic devices, while fatigue strength defines the material's ability to endure cyclic loading without fracture, which is indispensable in cardiovascular

stents and joint prostheses [154]. Several factors influence the mechanical strength of biomaterials. These include their chemical composition, crystallinity, porosity, and crosslinking density in the case of polymers. For instance, highly porous materials often exhibit lower strength but may promote better tissue integration. Likewise, the surrounding biological environment such as enzymatic activity, pH changes, and moisture can degrade the mechanical performance of materials over time [155]. In practical use, different classes of biomaterials exhibit varying mechanical behaviors. Metals such as titanium and stainless steel possess excellent tensile and fatigue strength, making them reliable for orthopedic plates and prostheses. Ceramics like hydroxyapatite demonstrate remarkable compressive strength, though they remain brittle, limiting their application mainly to dental implants and bone coatings. Polymers such as polyethylene and polylactic acid (PLA) generally have lower mechanical strength but offer high flexibility, making them useful for sutures, scaffolds, and drug delivery carriers. Composites, which combine metals, ceramics, or polymers, are engineered to balance strength, flexibility, and biocompatibility [156]. Matching the mechanical strength of a biomaterial to the mechanical environment of the target tissue is essential for long-term success. A mismatch, such as using a material that is too rigid, may cause stress shielding and bone resorption, while insufficiently strong materials may fracture under normal loading conditions. Therefore, optimizing mechanical strength is a key factor in ensuring both durability and biocompatibility of biomedical implants [157].

5.1.3. Biofunctionality:

Biofunctionality describes the capacity of a biomaterial to carry out its intended biological function within the body without inducing harmful effects. Unlike mechanical or chemical characteristics, this property focuses on the interaction between the material and living systems, ensuring that it supports specific roles such as tissue repair, drug delivery, or biosensing [158]. A biomaterial demonstrates biofunctionality when it not only integrates into the host environment but also enhances desired biological processes. For instance, orthopedic implants achieve biofunctionality by encouraging bone integration, while tissue engineering scaffolds exhibit it by supporting essential cellular activities like adhesion, proliferation, and differentiation [159]. In biosensors, biofunctionality is reflected in their ability to selectively and sensitively detect biological signals or analytes, thus providing accurate measurements. Although related to biocompatibility, biofunctionality extends beyond simple tolerance by requiring active contribution to biological performance. This can be achieved through strategies such as surface engineering, incorporation of bioactive compounds, or designing nanoscale structures that imitate natural extracellular matrices [160].

5.1.4. Degradability:

One of the essential properties of biomaterials is their degradability, which defines their capacity to undergo breakdown when exposed to physiological environments. This process can occur through hydrolytic, enzymatic, or oxidative mechanisms depending on the biomaterial's composition [161]. Degradable biomaterials are especially useful in temporary medical devices, such as scaffolds, sutures, or controlled drug delivery systems, because they gradually disintegrate after serving their purpose [162]. A key benefit of degradability is that it removes the need for a secondary surgery to extract the implanted material, reducing risks, cost, and patient discomfort [163]. For instance, synthetic biodegradable polymers like polylactic

acid (PLA) and polyglycolic acid (PGA) are widely applied since they break down into natural metabolites such as lactic acid and glycolic acid [164]. Similarly, natural polymers such as collagen and chitosan are enzymatically degraded, making them highly suitable for tissue regeneration and wound treatment [165]. Nevertheless, controlling degradation is crucial. If a material degrades too quickly, it may lose its function before tissue healing is complete, while slow degradation can trigger inflammation or encapsulation [166]. To address this, researchers tailor degradation rates by chemical modification, cross-linking, or copolymerization so that the biomaterial's lifespan aligns with the clinical requirement [167]. Therefore, degradability plays a decisive role in the success of biomaterials, as optimizing it ensures the safe and efficient development of resorbable medical devices and implants that support natural healing [168]. Table 3 gives challenges and limitations of bionanotechnology in food industries.

6.0. Research Gaps

6.1.1. Toxicity and Human Health Implications:

There is a critical lack of in vivo and long-term, chronic toxicity data regarding the ingestion of manufactured nanomaterials. While in vitro studies show high reactivity, data on how nanoparticles accumulate in organs (liver, kidney, spleen) or cross the blood-brain barrier is insufficient [177].

6.1.2. Nanoparticle Migration in Complex Food Matrices:

Inconsistent and conflicting data exist regarding the migration of nanoparticles from active packaging into various food types (fatty vs. acidic vs. high-moisture foods). Most studies use simple food simulants rather than actual food matrices [178].

6.1.3. Environmental Impact and Biodegradability:

The long-term environmental fate of inorganic nanoparticles (Ag, ZnO) released during disposal is not fully understood. Furthermore, some nanoparticles can inhibit the biodegradability of bio-based plastics, acting contrary to the goal of sustainability.

Scalability and Economic Feasibility: Many advanced bionanomaterials (e.g., nanofibers, nanoemulsions) show great promise in laboratory settings but are not economically viable for mass production compared to conventional plastics [179].

6.1.4. Regulatory Frameworks:

There is an absence of standardized, global regulatory guidelines specifically defining "nano-foods" or establishing mandatory labeling, with regulations varying significantly between the EU, USA, and other regions.

Consumer Acceptance and Safety Perception: Limited transparency and lack of clear labeling, coupled with consumer skepticism, hinder the commercial adoption of nanofood products [179].

7.0. Future Perspectives

The application of bionanotechnology and biomaterials in the food industry is poised for significant advancement, potentially transforming food production, packaging, distribution, and personalized nutrition. In the near term, approximately the next five years, we can expect niche commercial deployment of nano-enabled technologies, particularly in smart packaging and targeted nutrient delivery systems. Wider adoption over the next decade will largely depend on regulatory frameworks, comprehensive safety assessments, industrial scalability, and the development of circular-economy supply chains [180]. Emerging smart and active packaging solutions will increasingly incorporate low-cost nanosensors capable of detecting microbial contamination, freshness, and temperature variations in real time. These sensors, such as electrochemical, plasmonic, and fluorescent types, are anticipated to be implemented in high-value perishable foods as integration costs and power requirements decrease [181]. Nano and micro encapsulation technologies will continue to improve, allowing precise delivery of flavors, antioxidants, antimicrobials, and micronutrients. Such systems can enhance the stability and controlled release of bioactive compounds, protecting probiotics from gastric degradation and improving the overall functionality of foods, including personalized nutrition products [77]. The development of antimicrobial packaging using nanostructured biopolymers, including chitosan nanoparticles and cellulose-based composites, offers the potential to reduce spoilage and pathogen transfer without relying on chemical preservatives. Additionally, composites created from upcycled waste materials are gaining attention due to their sustainability and functional performance [182]. Sustainable biomaterials, such as bio-based and compostable films, are expected to approach or match the barrier and mechanical properties of traditional petroleum-based polymers. Utilizing agricultural or food waste as feedstock, for example chitin or lignocellulosic residues, will further

Table 3. Challenges and Limitations of Bionanotechnology and Biomaterials in food industries

Category	Bionanotechnology	Biomaterials	Reference
Safety and Health Concerns	Some nanoparticles may pose health risks, and their long-term effects in the human body are not yet fully understood.	Certain biomaterials may cause allergic reactions or trigger the immune system in sensitive individuals.	[169]
Regulatory Issues	There are few consistent international rules for using nanomaterials in food, making approval and adoption difficult.	Gaining legal approval for new biomaterials, especially for food contact or edible uses, is often a lengthy process.	[170]
High Cost and Production Limits	Developing and producing nanotechnology-based food systems can be expensive and hard to scale for widespread use.	Natural biomaterials may be costly to process, and large-scale production remains a challenge.	[171]
Environmental Uncertainty	The breakdown of nanoparticles in the environment is not well understood and may pose risks if they accumulate.	Some 'biodegradable' materials only break down under specific conditions and may not decompose quickly in all environments.	[172]
Consumer Acceptance	Public awareness and understanding of nanotechnology in food are limited, leading to distrust or rejection.	Although more acceptable to consumers, biomaterials sometimes underperform compared to traditional plastics, raising concerns.	[173]
Physical Weaknesses	Some nanomaterials may not be durable or suitable for existing food systems due to weak structure.	Many natural biopolymers are not strong enough for packaging and are sensitive to moisture.	[174]
Instability in Food Systems	Nanomaterials may lose their effectiveness over time or when exposed to heat, pH changes, or processing.	Biomaterials can break down or interact negatively with food components under certain conditions.	[175]
Technical Barriers	Ensuring even distribution and lasting stability of nanoparticles in food systems is technically complex.	Biomaterials may lack flexibility in heat-based or high-speed industrial processes compared to synthetic materials.	[176]

support circular economy principles while reducing environmental impact [129]. Regulatory and safety considerations will be critical in determining the pace of adoption. Agencies such as EFSA emphasize the need for comprehensive migration studies, toxicological evaluation, and standardized characterization methods for engineered nanomaterials in food and food-contact materials. Without clear and reliable safety data, market adoption may be slowed, particularly in regions with stringent regulations [183]. Market adoption will likely be led by premium and health-focused product lines, including functional foods, ready-to-eat meals, and products requiring cold-chain logistics. Companies adopting these technologies can expect benefits such as reduced food waste, longer shelf life, and enhanced nutritional value. Supply chain adjustments, including the use of biomass-derived feedstocks and partnerships with sensor technology firms, will be necessary for scaling production [184]. Environmental and circularity considerations will play an increasing role. Although biobased materials are considered more sustainable, their overall impact depends on life-cycle performance, including land use, compostability, and compatibility with recycling infrastructure. Failure to account for environmental persistence or allergen release from new materials could hinder their acceptance [185]. Consumer acceptance will also be crucial. Transparency, clear labeling, and third-party validation will influence public trust. Ethical issues may emerge around packaging that tracks product or user behavior, equitable access to nano-enhanced foods, and environmental justice [186]. Key research gaps remain, including standardized nanoscale characterization, reliable migration studies in complex food matrices, long-term environmental fate assessments, and techno-economic evaluations for large-scale biomaterial production using waste feedstocks [187]. In summary, the next 5–15 years are expected to see gradual but substantial integration of bionanotechnology and biomaterials into the food sector, with milestones including pilot commercialization, wider adoption as costs decline, and the establishment of mature circular systems for sustainable packaging. Success will depend on robust safety data, regulatory clarity, environmental stewardship, and public acceptance [132].

8.0. Conclusion

This paper discussed the roles, advantages, and limitations of bionanotechnology and biomaterials in food industries. The convergence of bionanotechnology and biomaterials represents a transformative advancement in the food industry, offering innovative solutions to longstanding challenges in food quality, safety, shelf-life, sustainability, and consumer health. Both fields rely on interdisciplinary principles drawn from biology, chemistry, materials science, and engineering to design functional systems at the molecular and nanoscale levels. Bionanotechnology has enabled the development of smart packaging, nanosensors, nanoencapsulation, and active antimicrobial systems, enhancing real-time monitoring, controlled nutrient delivery, and food preservation. Its precision and responsiveness offer novel approaches to detecting pathogens, tracking food freshness, and tailoring nutrient release based on environmental conditions. Similarly, the use of biomaterials, especially those derived from renewable or natural sources, aligns with the global push for sustainable, biodegradable, and health-conscious alternatives to synthetic additives and petroleum-based packaging. Biomaterials such as chitosan, alginate, and polylactic acid have proven effective in producing edible coatings, biodegradable films, and functional delivery systems that maintain food integrity while minimizing environmental impact. Despite their promise, both domains face significant chal-

lenges, including scalability, cost, regulatory approval, and consumer acceptance. Concerns around nanoparticle toxicity, material stability, and long-term environmental effects must be addressed through rigorous research, transparent risk assessment, and harmonized policy development. Looking forward, the integration of bio-based materials with nanotechnology, particularly within smart and responsive food systems, offers unparalleled potential for personalized nutrition, real-time quality assurance, and zero-waste packaging. As research advances and regulatory frameworks mature, the synergy between bionanotechnology and biomaterials will undoubtedly play a central role in shaping the future of sustainable and intelligent food systems.

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