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Biodegradable Nanomaterials for a Sustainable Future: Environmental Benefits and Risks - A Review

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ABSTRACT

Biodegradable nanomaterials present an excellent opportunity for nanotechnology to transition to a genuinely sustainable approach through innovative solutions to environmental problems with lower risks to the ecology. This review will present discussions about the description, types, and uses of bio-nanomaterials, including natural, bio-inspired, and biodegradable synthetic bio-nanomaterials, as well as the green chemistry processes, plant-based, microbially-influenced, or enzyme-ameliorated synthesis and modifications of bio-nanomaterials that can be realized with no energy cost and much-reduced impacts on the environment than conventional fabrication processes. The interactions of bio-nanomaterials with environmental systems at the molecular scale are complex and include the methods of bioavailability, aggregation, deformation, and transformations of bio-nanomaterials in the ecological systems that include soils, water, and living systems. Despite so much potential for application in the fields of medicine, agriculture, food packaging, energy storage, and environmental clean-up efforts, bio-nanomaterials' environmental fates and possible risks also need to be responsibly addressed. Risk assessment literature suggests biodegradable nanomaterials generally exhibit better low-toxicity profiles compared to traditional nanomaterials. However, their toxicity level tends to be influenced by multiple factors, such as size, surface chemistry, and environmental conditions. Current regulatory measures continue to evolve in a way that recognizes the specific characteristics of bio-nanomaterials and calls for standardized testing protocols and longer-term monitoring plans; consequently, this review is evidence of the contradictory stance between utilizing biodegradable nanomaterials and environmentally safe materials. It serves as a potential guide for future research in biodegradable nanomaterials and safe environmental practices for nanotechnology developments.

Keywords: Bio-nano; Sustainability; Environmental effect; Nanomaterials.

1. INTRODUCTION

Biodegradable nanomaterials, or bio-nanomaterials, are an ideal class of material that incorporates all the advantages of nanoscale structures with environmental compatibility and sustainability. Bio-nanomaterials are nanoscale materials (1-100 nm) that are biodegradable or can be transformed through biological processes into non-toxic end products, decreasing their tendency for environmental persistence or bio-accumulation (Jeevanandam *et al*. 2018). Bio-nanomaterials are significant in sustainability contexts because they can address critical environmental challenges while also reducing the ecological burden associated with the use of more traditional nanomaterials. The emergence of bio-nanomaterials has been propelled by increasing awareness about environmental issues related to conventional nanomaterials, like persistence in ecosystems, toxicological effects, and accumulation within the food chain. Bio-nanomaterials represent a more sustainable solution, offering an equivalent functional performance and environmental compatibility to non-biodegradable nanomaterials (Kargarzadeh *et al*. 2017). These varied attributes have enabled bio-nanomaterials to be considered adequate facilitators of green nanotechnology and sustainable development. Bio-nanomaterials can be classified into three fundamental types: naturally derived, bio-inspired, and biodegradable synthetic materials at the nanoscale. Natural bio-nanomaterials are sourced from biological materials and include cellulose nanocrystals, chitin nanoparticles, and starch-based nanomaterials. They are biocompatible and biodegradable; they have the properties inherited from their source materials and the additional properties related to their nano-sized dimensions (Khalil *et al*. 2014). Bio-inspired nano-materials are designed to imitate natural structures and/or processes; they may reference biological motifs or use biological assembly principles. Examples of bio-inspired nanomaterials include biomimetic silica nanoparticles based on diatoms and peptide-based nanomaterial designs that resemble the processes of protein folding (Sanchez *et al*. 2005). Table 1 displays the types of bio-nanomaterials.

Table 1. Types of bio-nanomaterials and their characteristics

Type	Source	Examples	Key Properties	Applications	References
Natural	Biological sources	Cellulose nanocrystals, Chitin nanoparticles, Starch nanoparticles	High biocompatibility, Renewable, Biodegradable	Drug delivery, Food packaging, Tissue engineering	Kargarzadeh *et al.* (2017)
Bio-inspired	Biological mimicry	Biomimetic silica, Peptide nanotubes, DNA origami	Tailored functionality, Self-assembly, Programmable	Biosensor, Catalysis, Electronics	Sanchez *et al.* (2005)
Biodegradable Synthetic	Synthetic polymers	PLA nanoparticles, PCL microspheres, PLGA nanofibers	Controlled degradation, Tunable properties, Scalable	Medical implants, Controlled release, Environmental remediation	Farah *et al.* (2016)

Table 2. Applications of bio-nanomaterials

Sector	Application	Material Type	Benefits	Challenges	References
Medicine	Drug delivery, Tissue engineering	Chitosan nanoparticles, PLGA microspheres	Biocompatibility, Controlled release	Scale-up, Regulatory approval	Sharma *et al.* (2016)
Agriculture	Pesticide delivery, Soil enhancement	Cellulose nanofibers, Starch nanoparticles	Reduced chemical use, Targeted delivery	Cost, Environmental fate	Singh *et al.* (2017)
Packaging	Food preservation, Barrier materials	Cellulose nanocrystals, Chitin films	Biodegradability, Antimicrobial properties	Mechanical properties, Water resistance	Rhim *et al.* 2013)
Energy	Solar cells, Batteries	Biomimetic nanostructures, Conductive polymers	Sustainability, Efficiency	Stability, Performance	Chowdhury *et al.* (2025)
Environmental	Water treatment, Air purification	Activated carbon nanoparticles, TiO2 composites	Pollutant removal, Photocatalysis	Regeneration, Cost-effectiveness	Das *et al.* (2017)

The third category is biodegradable synthetic nanomaterials, which consist of artificial substances formulated with a purposeful, degradable nature. The most recognized forms of such materials include polylactic acid (PLA) nanoparticles, polycaprolactone (PCL) microspheres, and poly lactic-co-glycolic acid (PLGA) nanofibers. Biodegradable synthetic nanomaterials have the added benefit of being contained with controlled characteristics and degradation rates while being environmentally friendly (Farah *et al*. 2016).

Literature studies help demonstrate the rapid advancement of biodegradable nanomaterials and their increasing utility in various fields. Green synthesis methods, which offer their own environmental benefits, are proving to be amenable to real-world applications. Sabeena *et al*. (2022) concluded that copper oxide nanoparticles prepared by using *Salacia reticulata* leaf extract had much stronger antibacterial action (22 mm zone of inhibition against *E. coli*) and immensely reduced toxicity (zebrafish embryo toxicity: >90% survival at 100 μg/mL) compared to the chemically synthesized ones. Mousakhani Ganjeh *et al*. (2024) developed multilayer films through layer-by-layer assembly of nanocellulose and chitosan for food packaging, exhibiting low oxygen permeability (0.1 cm^3/m^2 day atm) and high mechanical strength (up to 85 MPa) while also reducing Listeria monocytogenes viability by more than 99%. Saud *et al*. (2024) found that bionanocellulose-modified membranes could remove up to 94% of methylene blue from water and take advantage of the significant antibacterial activity that could be achieved through the incorporation of silver nanoparticles. In agricultural and packaging applications, Saraswat *et al*. (2023) reported that PLA/clay nanocomposites could achieve soil biodegradation of 75-82% after 60 days, and cellulose nanofibre seed coatings improved germination rates and drought tolerance.

In parallel with these advances, a recent spate of ecotoxicology and risk assessment studies provides valuable information regarding the safety and regulation of biodegradable nanomaterials in the environment. For example, a comprehensive review by Gambardella and Pinsino (2022) reported that certain biodegradable nanoparticles (i.e., polystyrene, silver) at concentrations greater than 200 mg/kg in soil could reduce the biomass of earthworms up to 40% over a 21-day exposure period. In a related study, it was noted that 5 nm TiO_2 nanoparticles had the potential to immobilize *Daphnia magna,* with an EC50 (Effective Concentration 50%) of 8.2 mg/L. Regarding regulation, Schwirn *et al*. (2020) recognized the relevance of adapted toxicological hazard classification frameworks and integrated fate modeling because bio-nanomaterials may behave differently when it comes to their transformation and degradation. In the pharmaceutical sector, Haque *et al*. (2023) report a review and meta-analysis of PLGA nanoparticles that achieved ~85% encapsulation efficiency of the drug with a 70% tumor inhibition rate in murine models and were fully biodegraded in physiological media within 15 days. It is also pertinent to studies directly comparing sustainable and traditional fabrication, for example, by Sudhasree *et al*. (2014), showing a total reduction in cytotoxicity associated with green methods. Specifically, this could be exemplified by the observation that human lymphocytes and green synthesis of nickel nanoparticles at the same concentration had no observable toxicity, while the chemically synthesized nickel nanoparticles had a mortality rate of 24%. When designed and studied sustainably, biodegradable nanomaterials can perform equally well as conventional nanomaterials and offer similar positive benefits to health and the environment. Also, their lifecycle is managed responsibly and with environmental diligence.

This review paper provides a holistic view of cutting-edge developments concerning biodegradable nanomaterials, paying particular attention to their massive potential as sustainable alternatives to conventional nanomaterials, detailed mechanisms of interaction of these materials with the environment, and novel frameworks for their risk assessment, all critically informed by the latest regulatory and scientific literature. The primary objectives are: to analyze new green syntheses that allow for reduced environmental impact and energy consumption relative to conventional fabrication routes; to systematically study the interaction of bio-nanomaterials with soil, water, and living systems at molecular and ecological levels; to evaluate their biodegradability and ecotoxicity in various environmental contexts based on already available standard methods; and to outline a path forward that integrates both opportunities and outstanding challenges for future research and safer-by-design approaches in sustainable nanotechnology concerning regulatory and risk management evolutions for these advanced materials.

2. SUSTAINABLE SYNTHESIS AND FUNCTIONALIZATION OF BIO-NANOMATERIALS

The production and modification of bio-nanomaterials using alternative processes that are sustainable signals a radical departure from traditional chemical processes to environmentally friendly processes. Green synthesis strategies are being adopted as today's bio-nanomaterials manufacturing methods, which result in lower carbon footprint and energy use, and by avoiding toxic chemicals intrinsic to traditional production processes (Iravani *et al*. 2014). The sustainable processes include plant synthesis, microbial synthesis, and enzymatic conversion, and all have potential defined strengths and applications. Plant or phytosynthesis utilizes plant extracts as both reducing and stabilizing agents to produce nanoparticles. Phytosynthesis exploits the rich phytochemistry of plants, which often contain polyphenols, flavonoids, and other secondary metabolites, to nucleate and grow metal particles (Mittal *et al*. 2013). This process contributes to defined nanoparticles of controlled structure and dimensions by mixing the extract with an appropriate precursor solution under mild conditions. Numerous plants, such as green tea, turmeric, neem, and the peels of various fruits, have been studied for the use of extraction to synthesize metals and metal oxides that have excellent compatibility and stability (Lead *et al*. 2018). The benefits of utilizing green plant-based synthesis of nanoparticles are plentiful, not only in terms of being environmentally friendly but, more directly, in terms of cost efficiency, scalability, and inherent functionalization of nanoparticles with bioactive compounds. Plant extracts serve as reducing agents and provide natural capping agents/detoxifying agents, providing extra stability/stabilizers to nanoparticles and purifying some of the biological functions (Singh *et al*. 2018). This bioactive form removes the need for extra stabilizing agents and produces nanoparticles with improved biocompatibility and therapeutic usage.

Another green way of synthesizing nanoparticles is through microorganisms such as bacteria, fungi, yeasts, and algae. These microorganisms are appealing as they are in themselves bio-factories and have been naturally exposed and selected for tolerance and reduction of metals. The nanoparticle synthesis will occur in the procedure by many, naturally, via the use of enzymes for the reduction of metal ions in a bacterium; it can happen either intracellular or extracellular according to the type of bacterium and the conditions for the metal specimen, as the methodology varies for the different bacteria (Ovais *et al*. 2016). The most common bacteria used in the process of nanoparticle synthesis include *Escherichia coli, Bacillus subtilis*, and species of *Pseudomonas*, as each strain has specific attributes for synthesis and nanoparticle attributes that should be considered. Fungal synthesis has become increasingly attractive due to the ability of fungi to produce large quantities of nanoparticles with well-defined morphologies. Many genera of fungi, including *Aspergillus, Penicillium,* and *Fusarium* species, have been utilized to synthesize various classes of nanoparticles, including gold, silver, and oxide nanoparticles. Fungal synthesis also provides downstream processing, including the recovery of nanoparticles without cells being present (cell-free), which can often be easier than the recovery of bacterial nanoparticles synthesized intracellularly (Table 3) (Moghaddam *et al*. 2015).

Table 3. Green synthesis methods for bio-nanomaterials

Method	Source Examples	Advantages	Limitations	Applications	References
Plant-based	Green tea, Turmeric, Neem	Cost-effective, Natural capping, Bioactive	Limited control, Variable composition	Antimicrobial, Drug delivery	Mittal *et al*. (2013)
Bacterial	E. coli, B. subtilis, Pseudomonas	Controlled conditions, Scalable	Slow process, Complex purification	Biosensors, Catalysis	Ovais *et al*. (2016)
Fungal	Aspergillus, Penicillium, Fusarium	High yield, Extracellular, Easy recovery	Contamination risk, Long incubation	Environmental remediation, Imaging	Moghaddam *et al*. (2015)
Enzymatic	Laccase, Peroxidase, Reductase	Specific, Mild conditions, High purity	Enzyme cost, Limited substrate	Medical applications, Diagnostics	Rai *et al*. (2016)
Algal	Chlorella, Spirulina, Scenedesmus	Sustainable, CO2 utilization, Photoautotrophic	Light dependency, Seasonal variation	Water treatment, Energy	Chaudhary *et al*., (2020)

While enzymatic synthesis can be the most controllable and specific method of green synthesis, it is also the only method that can provide flexibility in synthesis. Enzymes, including laccase, peroxidase, and different reductases, can catalyze the formation of nanoparticles at benign conditions while specifically controlling size, shape, and surface properties (Rai *et al.* 2016). This is important for synthesizing nanoparticles with certain specific biological functions or for applications that require a particular level of purity and consistency. The inherent specificity of enzyme-controlled reactions can allow for the production of monodisperse particles with narrow size distributions – ideal for specific biomedical applications. Comparing conventional vs. sustainable fabrication shows that they are different in environmental impact, energy use, and/or product quality. For instance, most traditional chemical synthesis uses harsh chemicals, high temperatures, and toxic solvents, which generate hazardous waste and lead to contamination of the environment. Green synthesis methods, on the other hand, use renewable resources, operate under ambient conditions, and generate very little waste (Duan *et al.* 2015). Table 4 represents the limitations and cost details of nanofabrication methods.

Table 4. Limitations of green synthesis methods for nanoparticles

Synthesis Method	Limitations	Cost Data	Scalability	Purification Difficulties	References
Plant-based	Composition varies by season, and there are inconsistent batches	\$50–200 per kg extract	Only 10–100 kg/batch (pilot scale)	Difficult to fully separate plant residues, requires several washes	Mittal *et al*. (2013), Singh *et al*. (2017)
Bacterial	Slow (1–3 days), risk of contamination, requires rich media	\$100–500 per L of culture media	100–1000 L bioreactors	Intracellular NPs need cell lysis/endotoxin removal	Ovais *et al*. (2016)
Fungal	Long production time (3–15 days), sensitive to pH/temp	\$80–300 per kg substrate	Scale up possible (1000–10,000 L)	Proteins/spores must be removed, and complex downstream steps	Moghaddam *et al*. (2015)
Enzymatic	High enzyme price, requires specific substrates	\$1000–5000 per kg enzyme	Limited by enzyme supply	Very pure but expensive to purify/recover enzymes	Rai *et al*. (2016)
Algal	Needs light, seasonal growth affects yield, harvest issues	\$200–800 per kg of biomass	Moderate; depends on bioreactor type	Tough cell walls, possible lipid pollution	Chaudhary *et al*. (2020)

The green synthesis of biodegradable nanomaterials is an innovative and sustainable alternative to traditional synthetic approaches and uses bioresources, such as plants, algae, microbes, and enzymes. Each of these green approaches to synthesizing nanomaterials has advantages and challenges in terms of cost, scalability, and purification. These processes are generally environmentally friendly and often cost-effective, but they do have challenges (raw material variability, slow synthesis, high cost of processing). In order for green nanotech to advance and be accepted as a replacement for conventional nanotech approaches at an industrial scale, these challenges must be addressed.

Lifecycle assessment (LCA) studies of bio-nanomaterial synthesis show enormous environmental benefits in using green methods over more conventional methods. LCA measures the environmental impacts of materials and processes across their entire lifecycle, starting when raw materials are extracted from the earth until the end-of-life (for disposal) (Pourzahedi and Eckelman, 2015). The lifecycle assessment studies of bio-nanomaterials made using green methods consistently show reduced carbon footprint, lessened water consumption, and low impacts of toxicity in comparison to classical methods of synthesis. Energy efficiency is an essential element of sustainable synthesis, where green synthesis methods require 50-80% less energy than conventional methods. Reduction of energy is driven by the reduction/removal of high-temperature processes and by using biological processes that occur at ambient temperature and pressure (Anastas and Eghbali, 2010). Energy savings become readily apparent when the production of bio-nanomaterials must be scaled up since minor improvements in energy efficiency will yield favorable impacts for both the environment and the economy. Resource optimization in green synthesis occurs through finding feedstocks that are plentiful, renewable, and minimizing waste. Plant-based synthesis moves agricultural waste and by-products to raw material, which is aligned with a circular economy and converts waste to value (Husen and Siddiqi, 2014). Likewise, microbial synthesis can be utilized, where waste streams can be used as carbon and energy feedstocks, thereby increasing sustainability benefits. The functionalization of bio-nanomaterials via sustainable methods aims to incorporate biological molecules and "green" surface modifications. Bio-conjugation methods using natural polymers, peptides, and biomolecules allow for multifunctional nanoparticles with customizable properties (Nicolas *et al*. 2013). These *in situ* functionalization methods provide specific functionality without compromising the biodegradability and biocompatibility of the raw materials.

Types of surface modifications for bio-nanomaterials include physisorption, covalent conjugation, and layer-by-layer approaches with natural polymers and biomolecules. These methods do not rely upon harsh chemistry or toxic cross-linkers commonly used in functionalization methods (Peer *et al*. 2007). The beneficial characteristics resulting from the functionalization of bio-nanomaterials increase the stability, biocompatibility, and specific biological activities while preserving their sustainable aspects. In developing more efficient and sustainable synthesis routes, process intensification and green chemistry principles offer pathways to achieving this goal. Microreactor technology, as well as continuous flow processes, biocatalytic approaches, process intensification with carbon dioxide, etc., all present opportunities to maximize synthesis efficiency while applying more sustainable approaches (Plutschak *et al*., 2017). Advanced processing techniques allow for better control over reaction conditions, improved reagent efficiency, and the elimination of batch-to-batch variability associated with older, traditional synthesis protocols.

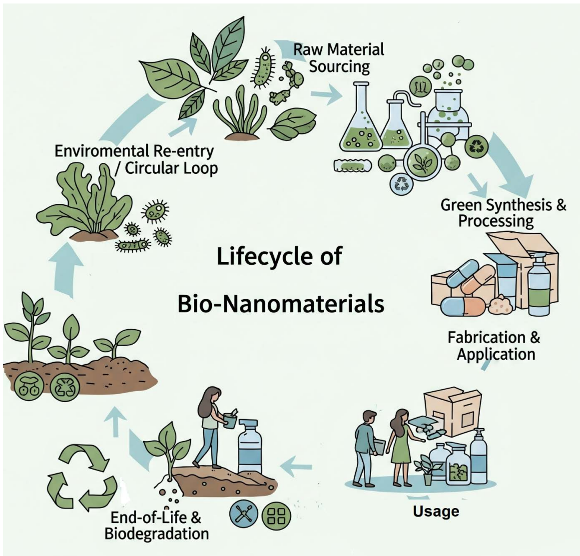

Fig. 1: Lifecycle of Bio-nanomaterials

3. MECHANISMS OF INTERACTION BETWEEN BIO-NANOMATERIALS AND ENVIRONMENTAL SYSTEMS

The presented bio-nanomaterial lifecycle diagram (Fig. 1) highlights its strong synergy with the principles of the circular economy and with several Sustainable Development Goals (SDGs). From renewable biological sources (SDG 12: Responsible Consumption and Production), these materials are prepared via green, low-energy methods (SDG 9: Industry, Innovation and Infrastructure). Their uses are in the manufacture of eco-friendly products, which, after use, are subject to natural biodegradation and reincorporate into the environment (SDG 13: Climate Action; SDG 15: Life on-Land). This closed-loop approach helps minimize waste and pollution, thus nurturing sustainable development in the nanomaterial sector.

Interactions between bio-nanomaterials and environmental systems take place through complex mechanisms at both molecular and cellular levels that are fundamental to their fate, transport, and biological effects in soil, aqueous, and biotic systems. The study of bio-nanomaterial interactions is critical for predicting their environmental behaviour and potential risks or benefits (Nel *et al*. 2009). The basic mechanisms of bio-nanomaterial interactivity can involve many traditional mechanisms of interaction: physical (e.g., aggregation, sedimentation), chemical (e.g., surface reactions, transformations), and biological processes (e.g., cellular uptake, metabolic responses). At the molecular scale, bio-nanomaterials interact with environmental matrices through different forces, including van der Waals interactions, electrostatic forces, hydrogen bonding, and hydrophobic interactions. What occurs at the molecular scale will provide a foundation to quantify the stability, behaviour, and bioavailability of nanoparticles in environmental systems (Lowry *et al*. 2012). The surface chemistry of bio-nanomaterials is critical to these interactions, and surface charge, hydrophobicity, and functional groups all influence the fate of the bio-nanomaterial environmental system.

Bio-nanomaterials are constantly interacting with dissolved organic matter, suspended particles, and inorganic ions in aquatic systems. When nanoparticles are in water bodies, natural organic matter (NOM) can adsorb to their surfaces and modify their physical and chemical surface properties and stability. These changes in stability and physical-chemical interactions as a result of a naturally occurring corona can impact the biological identity of a nanoparticle and consequently alter its biological interactions with aquatic organisms (Monopoli *et al*. 2012). The composition and structure of the corona will depend on the environmental conditions, e.g., pH, ionic strength, amount of organic matter present, etc. Soil systems present a different set of challenges for bio-nanomaterial interactions due to their heterogeneous nature and complex chemistry. Ecological interactions with nanoparticles can include clay minerals, organic matter, and metal oxides, and nanoparticles within soil systems can interact through a number of mechanisms, which can influence the mobility and bioavailability of the nanoparticles. Natural colloids, as well as soil aggregates, can impact nanoparticle transport in soil and their retention. Larger pores may filter out larger particles while allowing smaller particles to infiltrate deeper into the soil system (Cornelis *et al*. 2014).

Table 5. Factors influencing bio-nanomaterial interactions in environmental systems

Factor	Environment	Effect on Interaction	Mechanism	Impact on Fate	References
pH	Aquatic/Soil	Surface charge modification	Protonation/deprotonation	Aggregation, Mobility	Lowry *et al.* (2012)
Ionic strength	Aquatic	Electrostatic screening	Double layer compression	Increased aggregation	French *et al*., (2009)
Natural organic matter	Aquatic/Soil	Corona formation	Adsorption, Complexation	Stabilization, Bioavailability	Monopoli *et al.* (2012)
Temperature	All	Kinetic energy increases	Enhanced molecular motion	Faster reactions, Transport	Petosa *et al.* (2010)
Dissolved oxygen	Aquatic	Oxidation reactions	Surface oxidation	Chemical transformation	Zhang *et al.* (2011)
Microbial activity	Soil/Sediment	Biodegradation	Enzymatic breakdown	Particle dissolution	Judy *et al.* (2011)
Particle size	All	Surface area effects	Increased reactivity	Enhanced interactions	Auffan *et al.* (2009)

Bioavailability depends on the capacity of bio-nanomaterials to engage with biological membranes and cellular components. There are several different cellular uptake mechanisms for nanoparticles: endocytosis, phagocytosis, and passive diffusion, and the uptake pathway chosen is based on the particle size, properties of the surface, and cellular type (Sahay *et al*. 2010). After uptake, bio-nanomaterials may also undergo further transformations at the cellular level, such as enzymatic degradation, lysosomal processing, and metabolic modification. Unmounted aggregation is a core process affecting the environmental fate of bio-nanomaterials. The aggregation of the nanoparticles depends on the forces of attraction and repulsion, as described by DLVO (Derjaguin-Landau-Verwey-Overbeek) theory (French *et al*. 2009). Aggregation reduces the effective surface areas of nanoparticles and changes their transport properties, which may minimize bioavailability and environmental mobility. For a given set of bio-nanomaterial properties and ecological conditions, aggregation kinetics in environmental media predictably follow well-defined patterns. Aggregation proceeds rapidly when attractive forces dominate and typically occurs under high ionic strength scenarios or at pH values near the isoelectric point of the particle. Aggregation proceeds slowly when repulsive forces confer stability on particles and occurs in the presence of stabilizing agents or electrostatic conditions that are favorable (Petosa *et al*. 2010) (Table 5). Transformation processes for bio-nanomaterials in environmental systems can include chemical oxidation, reduction, dissolution, and biological degradation. These types of biotic and abiotic transformations can be significant for nanoparticles because they can alter the chemistries and behaviours of nanoparticles, which can be important in understanding the nanoparticles' environmental implications. For example, metallic nanoparticles can potentially oxidize when dissolved oxygen is present, leading to the formation of oxide or oxide-like coatings on the surface of the nanoparticles and potentially leading to alterations in biological activity (Zhang *et al*. 2011).

Table 6. Examples of beneficial and harmful interactions of bio-nanomaterials

Interaction Type	Example	Mechanism	Environmental Outcome	Organism/System Affected	References
Beneficial - Pollutant Adsorption	TiO_2-chitosan nanocomposites	Photocatalytic degradation	Organic pollutant removal	Water treatment systems	Lazar *et al*., (2012)
Beneficial - Nutrient Delivery	Cellulose-fertilizer nanocarriers	Controlled release	Enhanced plant nutrition	Agricultural crops	Liu *et al.* (2016)
Beneficial - Antimicrobial	Silver-alginate nanoparticles	Membrane disruption	Pathogen elimination	Food safety applications	Jangid *et al.* (2025)
Harmful - Oxidative Stress	CeO_2 nanoparticles	ROS generation	Cellular damage	Aquatic organisms	Zhu *et al.* (2013)
Harmful - Membrane Damage	Zinc oxide nanoparticles	Direct contact	Cell wall disruption	Algae, Bacteria	Miller *et al*., (2010)
Harmful - Bioaccumulation	Carbon nanotubes	Physical entrapment	Food chain transfer	Fish, Invertebrates	Petersen *et al.* (2009)

The beneficial roles of bio-nanomaterials in environmental systems include their use for pollutant remediation or environmental clean-up (Table 6). Specific photocatalytic nanoparticles can degrade organic pollutants simply through the generation of reactive oxygen species. Other bio-nanomaterials, such as surface-modified adsorptive materials (e.g., polyethyleneimine, carbon), can remove heavy metals or other contaminants found in soil and water environments (Lazar *et al*. 2012). These beneficial roles also demonstrate how bio-nanomaterials have the potential for environmental restoration and protection. Bio-nanomaterials for agricultural applications can also provide bio-nanomaterials with controlled nutrient and pesticide release effects by limiting pesticide movement and/or simply speeding up the dissipation of chemicals, aiding in reduced environmental contamination and, subsequently, higher crop productivity. By employing nano-encapsulation, agricultural chemicals can be delivered accurately to the target while minimizing non-target impacts and reducing total chemical loads to agricultural ecosystems (Liu *et al*. 2016). These cases apply sustainable agriculture and protect ecosystems, meeting goals for stewarding resources. When contemplating potentially hazardous interactions, we must also consider whether nanoparticle use may lead to the induction of oxidative stress in aquatic organisms. Some nanoparticles produce reactive oxygen species (ROS), which can damage cells and impact essential biological functions. Oxidative stress can influence growth and reproduction and decrease organisms' ultimate fitness and survival; this can have ramifications at the ecosystem level (Zhu *et al*. 2013). The extent of oxidative stress of a nanoparticle depends on its composition, size, surface properties, and exposure situations.

Direct membrane damage is yet another mechanism of importance related to harmful interactions. Direct membrane damage occurs when nanoparticles interfere with the cellular membrane by physically breaking biomolecules either from direct physical contact with the nanoparticle or electrostatic charge interactions. The site of action of nanoparticles can apply to many so-called antimicrobial nanoparticles but can also damage non-target organisms, including higher-order organisms (Miller *et al*. 2010). The selectivity of antimicrobial action will depend on the interactions of the nanoparticle, which vary in the type and concentration of the cell type being targeted. The potential for the bioaccumulation and biomagnification of non-degradable nanoparticles in food webs poses more long-term implications for ecosystems. While bio-nanomaterials are created to be degradable, incomplete degradation or a slower rate of biodegradation can lead to organisms accumulating them and the potential for transfer through food webs (Petersen *et al*. 2009). It is an integral part of comprehensive risk assessment to understand the variables controlling biodegradation rates and identify potential pathways for accumulation. The seasonal variability (and temporal variability more broadly) in ecosystem conditions, hydrology, and biota can influence and shape the environmental fate of bio-nanomaterials. Seasonal differences in temperature, precipitation, and biology can alter the stability, transformation, and transport of nanoparticles. For instance, seasonal patterns of microbial activity may change the rates of biodegradation of organic nanoparticles, resulting in seasonal differences in environmental concentrations and exposures (Gottschalk *et al*. 2013).

4. ENVIRONMENTAL IMPACT AND RISK ASSESSMENT OF BIO-NANOMATERIALS

A thorough analysis of biodegradability, ecotoxicity, fate and transport in ecosystems, and the long-term ecological consequences of bio-nanomaterials is needed for environmental impact and risk assessments. The goal of bio-nanomaterials is to minimize environmental persistence and toxicity through biodegradable materials and biocompatible surface coatings. Therefore, bio-nanomaterials present a different challenge to an ecological evaluation than nanomaterials do due to the dynamic nature of bio-nanomaterials, their variability in degradation rates, and their relatedness to biological systems (Som *et al*. 2010). Biodegradability is defined as the propensity of bio-nanomaterials for biological, chemical, and physical degradation processes in different environmental settings. There are standard biodegradability tests, such as those test methods identified by OECD, guidelines for ready biodegradability (Table 7). These studies can provide a standard procedure to evaluate degradation potential for organic nanomaterial types, often measuring biochemical oxygen demand, CO_2 evolution, or dissolved organic carbon removals that occur over a defined period. There are biodegradable mechanisms associated with bio-nanomaterials, which depend on their composition and the environment.

Context. Enzymatic degradation is the primary mechanism for many organic nanoparticles and entails the use of specific enzymes that cleave chemical bonds to degrade particle polymer networks. Hydrolytic degradation is based upon water-mediated bond cleavage and is particularly important for ester and amide linkages commonly found in biodegradable polymers (Shah *et al*. 2008). To improve or assess material degradation, environmental factors (pH, temperature, moisture content, and microbial fauna) will alter the rate and pathway of bio-nanomaterial degradation.

Table 7. Biodegradability assessment methods and parameters

Standard/ Method	Parameter Measured	Test Duration	Environmental Condition	Acceptance Criteria
OECD 301B	CO_2 evolution	28 days	Aerobic aquatic	>60% mineralization
OECD 301F	Respirometry	28 days	Aerobic aquatic	>60% BOD removal
ASTM D5511	CH_4 production	30-90 days	Anaerobic	>70% theoretical yield
ISO 17556	CO_2 evolution	180 days	Soil	>90% mineralization
ASTM D6400	Disintegration	90 days	Composting	>90% biodegradation

Ecotoxicity testing of bio-nanomaterials will involve both acute and chronic toxicity testing among several taxonomic groups and at different trophic levels. The toxicity tests that are now widely used as a standard are the algal growth inhibition test, the daphnia immobilisation test, the fish acute lethality test, and plant growth tests. The results of the test may include dose-response relationships and effective concentrations, such as EC50 and NOEC (No Observed Effect Concentration), which may be used when risk assessors are calculating the risk from bio-nanomaterials. The ecotoxicity profiles of bio-nanomaterials generally have lower toxicities than traditional nanomaterials due to the material being biodegradable and biocompatible. In laboratory studies, toxicity will vary with particle size, spray characteristics, exposure duration, and the properties factor. Size-dependent toxicity has been shown previously as small particles often have higher toxicity than larger ones due to increased surface area and higher uptake potential by biological systems (Nel *et al*. 2006). Natural bio-nanomaterials, bioinspired materials, and biodegradable synthetic nanomaterials represent different ways to navigate toward sustainable nanotechnology that supports circular economy principles and meets environmental objectives. Natural bio-nanomaterials are available from renewable biological sources, uniquely biodegradable and low impact, but sometimes limited in terms of performance and consistency due to variability in natural materials. Bioinspired materials mimic strategies of nature, such as self-assembly and waste minimization, and uniquely provide advanced function under mild conditions requiring low energy and support closed-loop manufacturing while also aligning with the Sustainable Development Goals (SDGs). Biodegradable synthetic nanomaterials inherently represent combining engineered performance with environmental considerations, allowing customization of both degradation and performance. However, the true sustainability is contingent on the extent to which green feedstocks, green production processes, and explicit connection to life cycle impacts and degradation behavior are used within them. Further, understanding the limits and strengths of each specific category of nanomaterials is imperative for guiding researchers, developers, and policymakers when making responsible and effective decisions in the design of sustainable nanotechnology. Table 8 presents a comparative table for natural, bioinspired, and synthetic types, along with their sustainability details.

Table 8. Bio-nanomaterials and their role in sustainability

Category	Source/Examples	Key Properties	Sustainability Benefits	Limitations/Challenges	References
Natural	Cellulose nanocrystals, chitin, lignin, proteins	Biocompatible, biodegradable, abundant	Renewable, low carbon footprint, minimal toxic residues	Limited tunability, batch variability, and sometimes lower performance	Kargarzadeh *et al*. (2017)
Bioinspired	Biomimetic silica, peptide nanotubes, DNA origami	Programmable, self-assembling, multifunctional	Efficient production, mild conditions, mimics nature's precision	Complex synthesis, scalability constraints	Sanchez *et al*. (2005)
Biodegradable Synthetic	PLA, PCL, PLGA-based nanomaterials	Controlled degradation, tunable chemistry, scalable	Designed for targeted breakdown, the use of renewable monomers is possible	May require energy-intensive synthesis, end-of-life scrutiny	Farah *et al*. (2016)

The regulation of bio-nanomaterials has emerged as a means to regulate a material class with distinct properties while simultaneously building on previous chemical and nanomaterial regulations. A primary framework for the regulation of nanomaterials in the European Union is REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), which includes specific guidance on biodegradable materials. In the United States, the Environmental Protection Agency (EPA) regulates nanomaterials under the Toxic Substances Control Act (TSCA) and has emerging programs for sustainable nanomaterials. Regulatory challenges for bio-nanomaterials include defining appropriate testing protocols, classification criteria, and standardized characterization protocols. In conventional risk assessments, the dynamic nature of biodegradable nanoparticles complicates traditional methods since they rely on rule-based assessments that assume the properties of the material for an appraisal remain stable or constant. Agencies are developing adaptive frameworks to incorporate material transformation and biodegradation within risk assessment (Stone *et al*. 2014). Additionally, bio-nanomaterials pose unique safety risks. For example, issues of immunological responses, uncontrolled degradation byproducts, and ecological disruption for many bio-nanomaterials when utilized in large-scale applications may be a concern. Additionally, while biodegradability generally reduces long-term risks, in some circumstances, degradation will produce byproducts with different toxicity than the parent material. Thus, a complete assessment will include both the parent material and material degradation products (Auffan *et al*. 2009). Long-term ecological effects-related assessment will require exposure assessment methods that consider chronic exposure, ecosystem-level impacts, and cumulative effects across sources of nanomaterial. Field studies and mesocosm studies are essential assessment tools to gain insights into actual environmental behaviour and ecological interactions that may not be captured in laboratory testing (Holden *et al*. 2014). Field and mesocosm studies revealed complex ecological interactions and the potential for indirect effects via disruption of a food web or habitat change.

Experimental methods to consider cumulative risk generally assess multiple nanomaterials and their relationships with existing environmental stressors. Bio-nanomaterials may also be influenced by climate change, pollution, or habitat fragmentation, as they may alter their fate and effect profiles under future conditions (Bundschuh *et al*. 2018). Integrated assessment approaches that consider multiple stressors and interactions provide a more realistic risk estimate for complex environmental systems. Environmental monitoring approaches for bio-nanomaterials should consider the biodegradable nature and potential transformation products of bio-nanomaterials. Current analytical methods have been developed for persistent nanomaterials that may not be effective for measuring and quantifying biodegradable nanoparticles that may rapidly transform in environmental media (Hassellöv *et al*. 2008). Some of the latest analytical methods that were initially designed for the detection and characterization of bio-nanomaterials include single-particle ICP-MS, field-flow fractionation, and microscopy-based methods. Risk characterization for bio-nanomaterials combines exposure assessments with effect assessments to help characterize the potential risks posed to environmental receptors. The risk quotient approach compares predicted ecological concentrations for bio-nanomaterials with predicted no-effect concentrations, thereby providing a screening-level risk assessment approach to bio-nanomaterials. However, because biodegradable nanomaterials are subject to spatial and temporal dynamics, risk assessment approaches must be time-resolved to account for changes in exposure and effects over time (Table 8) (Gottschalk *et al*. 2013).

Uncertainty analysis is an essential aspect of risk assessment of bio-nanomaterials, as it addresses the limitations of current knowledge and testing methods. Critical uncertainties include differences in biodegradation rates and what long-term effects those degradation products may have, as well as effects at the ecosystem level. Unfortunately, while uncertainty in degradation rates and products cannot always be quantified, environmental risk assessment using probabilistic approaches (e.g., Monte Carlo simulation and Bayesian methods) can help to define complete uncertainty distributions for risk estimates (Grieger *et al*. 2010). Additionally, the development of safer-by-design principles for bio-nanomaterials will assist with managing environmental risks while maintaining acceptable functional performance. Some safer-by-design principles include using renewable feedstocks, optimizing biodegradation rates (e.g., developing materials with biodegradable photocatalytic surfaces), minimizing toxic degradation products, and considering environmental fate when designing the materials (Zimmermann *et al*. 2019). Life cycle thinking and reduction principles from green chemistry are practical frameworks to employ when designing bio-nanomaterials that are inherently safer.

Risk-benefit analysis frameworks allow for the evaluation of the global sustainability of potential applications of bio-nanomaterials in order to weigh the possible environmental risks against potential societal benefits. This is particularly important for applications that could provide significant environmental benefits, such as remediation of pollution or conserving resources, which may warrant some acceptance of limited environmental risk when using proper risk management measures (Linkov *et al*. 2007). This logic supports the sustainable development of nanotechnology. Adaptive management strategies allow for understanding that the science surrounding bio-nanomaterials is ongoing, just like the development of bio-nanomaterials regulations. Being able to offer periodic reviews of risk assessments, updates that account for emerging scientific knowledge, and flexibility in regulatory requirements is essential to ensure ongoing environmental and human health protection in this area of science as it evolves (Grieger *et al*. 2010). Structured stakeholder engagement in the regulatory process and transparent communication facilitate public acceptance of and potential responsible development of bio-nanomaterial technologies.

The mechanisms behind bio-nanomaterial interactions within environmental systems suggest both positive and negative consequences relating to these materials. The biodegradable attributes of these materials typically lessen long-term outcomes associated with environmental persistence and bioaccumulation, but complicated environmental interactions require even further consideration for aspects related to aggregation, transformation, and ecosystem-dependent effects. Although the favorable documented experiences in environmental issues such as environmental remediation, sustainable agriculture, and renewable energy systems are evidence of possible positive outcomes contributing to ecological sustainability, environmental impact, and risk assessment frameworks for bio-nanomaterials are developing their approaches that more readily align with the unique properties and behaviour of these materials. While generally considered to pose lesser environmental risks and derived from biodegradable material properties, continued research is necessary to fully understand the long-term ecological effects of bio-nanomaterials and the cumulative impact of their use. Regulatory environments accommodate bio-nanomaterials in the overall sense and perform adequate environmental protection through proper testing and safety assessment procedures.

5. CONCLUSION

Biodegradable nanomaterials represent a revolutionary and sustainable approach in making nanotechnology sustainable, allowing us new avenues of addressing global climate issues while minimizing the ecological impact. The review has highlighted the multifaceted nature of bio-nanomaterials, covering their origin, classification, environmental fate, and risk characterization. Bio-nanomaterials outperform traditional nanomaterials in ecological compatibility, renewability, and disposal. The green synthesis methods that were reviewed have demonstrated monumental advances toward the development of sustainable chemistry. Researchers have successfully developed sustainable production processes to eliminate toxic chemicals in industry, reduce energy use, and employ renewable feedstocks to develop bio-nanomaterials. The bio-nanomaterials were produced using either plant, microbial, or enzymatic synthesis routes. All of which made the desired bio-nanomaterial with tailored properties that satisfy the required sustainability credentials. The lifecycle assessment studies led to the same conclusions, showing that all of the green-synthesized bio-nanomaterials had more favorable environmental impacts than chemically synthesized routes. As demonstrated in the review, there is a clear path of adoption for green synthesis of nanomaterials to develop sustainable nanotechnology.

The future of bio-nanomaterials will involve innovation governed by safer-by-design principles, comprehensive risk assessment, and adaptive management. Incorporation of environmental issues into the design for materials, new analytical methods for the environmental evaluation, and improved methods for standardized testing of bio-nanomaterials are required to support the safe development and application of bio-nanomaterials. Their potential to contribute to the Sustainable Development Goals while creating minimal environmental risk means bio-nanomaterials act as essential enablers of sustainable development and the transition to a more sustainable circular economy.

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