Chapter

Novel Acumens into Biodegradation: Impact of Nanomaterials and Their Contribution

Danushika C. Manatunga, Rohan S. Dassanayake and Renuka N. Liyanage

Abstract

Biodegradation is the most viable alternative for numerous health and environmental issues associated with non-biodegradable materials. In recent years, there has been considerable interest in biodegradable nanomaterials due to their relative abundance, environmental benignity, low cost, easy use, and tunable properties. This chapter covers an overview of biodegradation, factors and challenges associated with biodegradation processes, involvement of nanotechnology and nanomaterials in biodegradation, and biodegradable nanomaterials. Furthermore, current chapter extensively discusses the most recent applications of biodegradable nanomaterials that have recently been explored in the areas of food packaging, energy, environmental remediation, and nanomedicine. Overall, this chapter provides a synopsis of how the involvement of nanotechnology would benefit the process of biodegradation.

Keywords: Biodegradation, nanoparticles, food packaging, energy storage, environmental remediation, nanomedicine

1. Introduction to biodegradation

Sustainable development is a principle that is implemented to preserve the environment for the future generation while meeting the needs of the present generation. Environmental pollution is considered one of the significant barriers to sustainable development. Therefore, the drive for sustainable development must address environmental pollution by removing pollutants, restoring polluted areas, or using without affecting the unpolluted areas [1]. Biodegradation is identified as a key eco-friendly and economical way of sustainable development, which entails enzymatic degradation or a breakdown of complex organic matter into small molecules in the presence of microorganisms [2]. The microorganisms could also allow the biodegradation of organic matter in the presence of a growth substrate used as the primary source of energy and carbon source, a process called cometabolism [2]. The biodegradation process is an effective alternative for commonly applied waste disposal methods such as incineration and landfilling [3].

2. Key challenges associated with biodegradation process

Biodegradation may sometimes lead to incomplete mineralization of the total organic content, such as recalcitrant materials leaving unprocessed contaminants behind [4]. This could be due to the complex structure of the materials, higher molecular weight, crosslinking, shape, texture, surface area, and degradation rate [5]. For example, depending on the degree of crystallinity, orientation and packing of polymers, the degradation rate is severely affected. It has been observed that even under the same conditions, the degradation of amorphous regions of polycaprolactone (PCL) by filamentous fungi is much faster than the degradation of crystalline regions of PCL, where the amorphous regions may permit easy access to microbes during the degradation process [4]. Therefore, ensuring the complete or partial degradation of these complex substances to produce harmless products without secondary pollution is extremely important [5].

Additionally, the microbial biodegradation process also depends on various factors such as nutrient availability, microbe type, substrate properties, and environmental conditions such as pH, moisture content, and redox potential [6–8]. Generally, the redox potential relies on the presence of the electron acceptors at the active site, such as oxygen, nitrates, manganese oxides, iron oxides, sulfate, and triggering the aerobic or anaerobic biodegradation. Even though many of the microbes prefer physiological pH of 7.4 and a temperature of 37°C for their growth, certain microbes such as fungal species prefer an acidic environment. In contrast, some bacteria prefer relatively high temperatures for their optimal growth. Therefore, not exactly knowing the required growth conditions could be a significant factor contributing to the incomplete degradation of the substrate in some cases [7].

Furthermore, microbial metabolism in biodegradation is an energy transformation process that is solely governed by the functions of enzymes and the intermediates produced during the reactions [5]. Therefore, proper screening is required to identify the microbes with an inherent set of genes that are capable of degrading the contaminants, the factors and the conditions under which the population of these microbes could increase, and the synergic performance of these microbes with other technologies to establish an environmentally profitable biodegradation platform [9]. It has also been identified that more optimization procedures and scaling up are required for the biodegradation of large contaminated areas [10].

3. Role of nanotechnology in biodegradation

Biodegradable materials can be considered a preeminent group of materials that could also be called next-generation materials leading to zero global environmental pollution. Owing to this concern, the consumption of biodegradable materials, such as polymers, has increased two to three-fold in a broad spectrum of fields, including agriculture, automotive, packaging, energy and environment, and biomedical. But still, the contribution coming from the biodegradable polymers in said areas only accounts for 3–5% of total polymer consumption [11]. This lower contribution could be mainly due to the poorly addressed issues such as low durability, low performance, and high production cost [12].

In this context, combining the concept of biodegradation with nanotechnology could be identified as a more systemic and innovative approach to address the current issues with the biodegradation process [13]. Nanotechnology is an evolving branch of science that has diversified its application in many disciplines such as agriculture [14], healthcare [15], transportation [16], electronics [17], food [18], water purification [19–25], and security [26]. Nanotechnology involves manipulating matter in 1–100 nm nanoscale to create materials where at least one of the dimensions of the particles in the nano range [27]. The combined approach of nanotechnology-mediated biodegradation could address a wide range of potential applications in agriculture, food packaging, environmental remediation, and healthcare while accounting for reduced costs and no impact on environmental pollution [12]. Nanomaterials have proven effective as excellent adsorbents, sensors, and catalysts for biodegradation purposes due to their specific surface area and high reactivity [28].

Furthermore, the presence of nanoparticles and microbes that are actively engaged in the biodegradation process has paved the way in improving growth profiles of microbes by acting as biodegradation enhancers [29–32]. It has also been observed that the integration of nanotechnology with the enzymatic pathways in the biodegradation process could lead to profound activity and improved reusability of the enzymes [13]. Nanoparticles have also performed as effective sensor systems to detect the utilization of the raw materials and the production of specific products, which provided an inference on the progression of the biodegradation process [33]. Hence, this process of nano-biodegradation would ultimately involve the reduction of accumulating harmful non-biodegradable materials in the environment [34, 35].

3.1 Factors affecting the performance of nanomaterials during biodegradation

3.1.1 Properties of the nanomaterial

The chemical and physical interaction between the nanoparticles and the microbiota during the biodegradation is majorly influenced by the properties of nanomaterials such as size, shape, surface functionalization chemical structure, as they could influence the reactivity and stability of the nanomaterial [36, 37]. In addition, nanomaterials exhibit a quantum effect where less energy is required for associated chemical reactions [38]. Furthermore, the surface plasmon resonance exhibited by certain types of nanomaterials such as gold nanoparticles (Au NPs) [39] and silver nanoparticles (Ag NPs) [40] can also be used to detect and identify the contaminants. The smaller size of the nanomaterials also allows them to penetrate deeper into complex organic molecules [41].

3.1.2 Properties of the microorganisms and culture medium affecting the biodegradation

The performance of the nanomaterials during biodegradation also depends on the type of the organism, such as bacteria, fungi, protozoa and the type of enzymes used for the degradation of the contaminants [38]. Growth conditions such as pH, redox potential, temperature, ionic strength, solubility, presence or absence of electron acceptors in the culture medium also influence the activity and stability of the nanoparticles [13]. Therefore, proper control of the culture medium conditions to obtain a prolonged uninterrupted biodegradation procedure is necessary.

3.2 Types of nanomaterials used in biodegradation

Different types of nanomaterials have been utilized in the biodegradation process. **Table 1** summarizes the specific types of nanomaterials and their applications. Commonly used biodegradable nanomaterials include zero-valent metals, metal oxides, metal sulfides, nano clay, nanocomposites, carbon-based nanomaterials,

Type of the Nanomaterial	Type of degradation	Biodegradation process	Reference
Zero valent metals, oxides, sulfides			
I. Zero valent iron (nZVI)	Microorganism mediated- Organohalide-respiring bacteria (OHRB), sulfate reducing bacteria (SRB) and iron reducing bacteria (IRB)	nZVI provides suitable living conditions for the growth and activity of anaerobic bacteria to degrade organohalides, heavy metals	[42]
II. Zirconia (ZrO_2)	Microorganism mediated- *Pseudomonas aeruginosa*	Synthesis of ZrO_2 via *P. aeruginosa* for adsorption driven bioremediation of tetracycline	[43]
III. Silicon dioxide (SiO_2)	Microorganism mediated-Indigenous actinomycetes species isolated from the effluent contaminated site	Actinomycetes mediated synthesis of silica and use for adsorption and decolourisation of textile effluent	[44]
IV. Iron oxide (Fe_3O_4)	Microorganism mediated- *Microbacterium sp., Pseudomonas putida and Bacterium Te68R*	Enhance the consortium growth that involve in Low-Density Polyethylene (LDPE) degradation	[45]
V. Cadmium Zinc sulfide quantum dots (CdZnS QDs)	Microorganism mediated- *Escherichia coli*	Immobilization of nanoscale CdZnS QDs in to the extracellular matrix of bacterial biofilms which are later on used as catalysts for the degradation of nitro aromatic compounds	[46]
Nanoclay	Microorganism mediated- *Pseudomonas spp., Sphingomonas spp., Flavobacterium spp., Burkholderia spp., Rhodococcus spp., Mycobacterium spp., and Bacillus spp.*	Clay/modified clay minerals as effective adsorbents of PAHs/ volatile oxygen compounds (VOCs) to trigger the microbial mediated biodegradation	[47]
Nanocomposites			
I. Nanocellulose composites	Microorganism mediated- *Arthrobacter globiformis D47*	Bacteria decorated nanocellulose being used as a scaffold to grow the bacteria as well as to remove Diuron via biodegradation	[48]
II. Fe_3O_4/biochar composites	Microorganism mediated- *R. capsulatus*	Improve the adsorption capacity of photosynthetic bacteria as well as to improve the efficiency of bioremediation of wastewater	[49]
Carbon based nanomaterials			
I. Fullerene 60	Microorganism mediated- *Pseudomonas putida strain MK4 (DQ318885), Bacterium Te68R strain PN12 (DQ423487). P. aeruginosa strain PS1 (EU741797), P. putida strain PW1 (EU741798), and P. aeruginosa strain C1 (EU753182)*	Influence the growth cycle of LDPE, HDPE epoxy and epoxy silicon degrading bacteria and accelerate the polymer biodegradation process of bacterial consortia	[50]

Type of the Nanomaterial	Type of degradation	Biodegradation process	Reference
II. Carbon nanotubes (CNTs)	Microorganism mediated- *S. cerevisiae*, Actinomycetes	Immobilization of microbes for bioremediation of heavy metals	[51]
Biopolymer based nanomaterials			
I. Alginate beads	Microorganism mediated- *Acinetobacter sp., Bacillus circulans, Bacillus licheniformis, Brevibacillus brevis, Burkholderia cepacia, Leifsonia aquatica and Sphingomonas paucimobilis*	Improved the bacterial attachment required for oil bioremediation	[52]
II. Chitosan beads	Microorganism mediated- *Serratia sp. AC-11*	Remove polycyclic hydrocarbons by immobilizing the bacteria by improving the degradation rate	[53]
Nanofibrous materials			
I. Polyvinyl alcohol (PVA) and Polyethylene oxide (PEO) nanofibers	Microorganism mediated- *Pseudomonas aeruginosa ATCC 47085*	Provide suitable platforms for preservation of living bacterial cells and direct use for bioremediation of methylene blue	[54]
II. Cyclodextrin nanofibers	Microorganism mediated- *Lysinibacillus sp. NOSK*	Provide a matrix for the encapsulation of bacteria to perform bioremediation of heavy metals and reactive dyes	[55]
Biodegrading nanoparticles			
I. Polylactic acid (PLA) micelles	Physiological Enzymes mediated	Tumor targeting and efficient drug delivery	[56]
II. Polylactic glycolic acid (PLGA) micelles	Physiological Enzymes mediated	Use of thermosensitive and biodegradable triblock copolymer for temperature sensitive drug delivery for liver cancer	[57]
III. Polycarprolactone (PCL) nanoparticles	Physiological Enzymes mediated	Biodegradable nanocarriers for therapeutic compounds	[58]
IV. Chitosan nanoparticles	Physiological Enzymes mediated	Biodegradable nanocarriers for drug delivery diagnosis and other biological applications	[59]
V. Dendrimers	Physiological Enzymes mediated	Biocompatible, biodegradable delivery system against infections and cancer	[60]
VI. Liposomes	Physiological Enzymes mediated	Less toxic, biodegradable delivery systems for various diseases	[61]

Table 1.
Different types of nanomaterials used in biodegradation processes.

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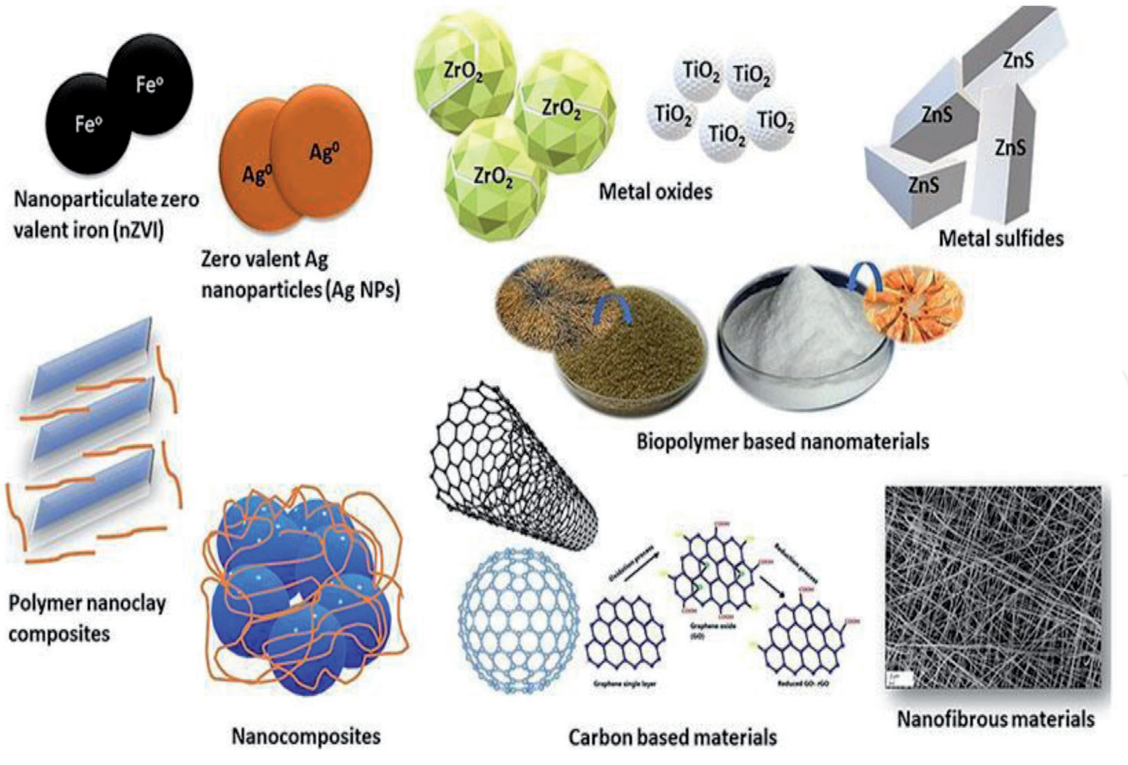

Figure 1.
Different types of nanomaterials widely used for biodegradation process.

biopolymer-based nanomaterials, and nanofibrous materials (see **Figure 1**). These nanomaterials can be synthesized using two different ways; one is the laboratory-mediated synthesis of nanoparticles (ex-situ) [29], and the other one is the in-situ synthesis of nanomaterials inside the microbes [62]. Besides, there could be another lineage of ex-situ synthesized nanomaterials, which are biodegradable in origin and mainly applied in the biomedical field as theragnostic agents [27]. After performing its' definite action including controlled drug delivery, imaging, implantation, tissue engineering) these nanomaterials undergo natural degradation upon the enzymatic attack inside the living cells [27].

However, the selection of the type of nanomaterial relies on the nature of the contaminants and the microorganism that mediates the biodegradation process [12].

4. Applications of biodegradable nanomaterials

Biodegradable nanomaterials or nanoparticles include two major types: nanomaterials directly synthesized from various biopolymers such as polypeptides, polysaccharides and polynucleotides; and metallic nanoparticles, which are colloidal particles encapsulated inside a polymer matrix. The selection of this biopolymer matrix is based on many factors, including the size of the nanoparticles, degree of biocompatibility and biodegradability, surface properties and functionality and the type of application [63]. These biodegradable nanoparticles are typically in the 10–500 nm size range. Widely used methods for the fabrication of biodegradable nanoparticles include emulsification, solvent evaporation, coprecipitation, desolvation, coacervation, electrospray and electrospinning [63]. Over the past few years, many studies have been conducted in various fields on the preparation and applications of biodegradable nanomaterial. However, the applications in food packaging, energy, environmental remediation, and nanomedicine are discussed in this section.

4.1 Food packaging

Packaging plays an imperative role in the food industry. The major function of packaging is protecting food from physical damage while handling, transporting and storage. Packaging materials also maintain the food quality by protecting against air, moisture, insects, light, and dust and prevent contamination from chemical and biological sources. Commonly used packaging materials include plastics, metals, paper and paper boards, glass, and other traditional materials. However, food packaging accounts for 50% of petroleum-based plastics [64]. Upon disposal, plastics remain in the environment taking many years to degrade. The fragments of plastics, also known as microplastics, enters the ecosystems via food chains causing growing environmental and health concerns. Therefore, there is a significant interest in the development of environmentally friendly food packing alternatives. Biodegradable nanoparticles have recently been employed for food packaging applications due to their simple synthesis route, non-toxicity, relative abundance, low cost, and eco-friendly nature. Following are recent food packing applications of biodegradable nanoparticles reported.

Pandey *et al.* prepared the biodegradable meat packaging material using fibrous composite nano-layers (PVA-CH-AgNPs-FCNLs) as an alternative for plastic packaging [65]. PVA-CH-AgNPs-FCNLs were synthesized by electrospinning of a blend of silver nanoparticles (AgNPs) incorporated chitosan (CH) and polyvinyl alcohol (PVA). PVA-CH-AgNPs-FCNLs showed bioactivity against *Escherichia coli* (gram-negative bacteria) and *Listeria monocytogens* (gram-positive bacteria) and extended the meat shelf-life by one week [65]. Ediyilyam and coworkers investigated biodegradable films prepared from silver nanoparticles (AgNPs) incorporated chitosan (CH) and gelatin (GE) polymer blend for food packaging applications [66]. They reported the improved physicochemical and biological functioning of the films upon incorporating the AgNPs. CH–GE–AgNPs films also displayed antimicrobial activity against bacteria and fungi and enhanced the shelf life of carrot pieces wrapped in them over ten days [66].

Kumar *et al*. developed low-cost biodegradable nanocomposite hybrid films containing chitosan, gelatin, and zinc oxide nanoparticles (ZnO NPs) [67]. ZnO NPs reinforced hybrid nanocomposites exhibited enhanced thermal stability, elongation-at-break (EAB), and compactness properties with antimicrobial activity against *Escherichia coli* (gram-negative) bacteria. The authors claimed that these hybrid nanocomposite films have the potential to be developed as biodegradable postharvest packaging of fresh fruits and vegetables [67]. Saral Sarojini and coworkers fabricated the biodegradable food packaging films from Mahua oil-based polyurethane (PU) and chitosan (CS), incorporated with zinc oxide nanoparticles [68]. They reported enhanced hydrophobicity of the film by about 63%, high UV-screening ability, high transparency, high degree of biodegradation of 86%, and antimicrobial resistance for the ZnO incorporated PU/CS films. ZnO-reinforced PU/CS films also extended their shelf life up to nine days upon wrapped with carrot pieces [68].

Starch-based (St) nanocomposite films prepared by incorporating silver (Ag), copper oxide (CuO) and zinc oxide (ZnO) nanoparticles (NPs) were tested for physicomechanical and antimicrobial properties by Peighambardoust *et al*. [69]. Ag/ZnO/CuO NPs incorporated starch-based films showed better antimicrobial and mechanical properties due to the synergistic effect. The authors reported the potential use of these starch-based nanocomposites as food packaging materials [69]. Colored biodegradable dye (methylene blue)-clay (montmorillonite)-nanopigment (DCNP)-polylactic acid (PLA) nanocomposite films were prepared and tested for various functional properties by Mahmoodi *et al*. [70]. The PLA-DCNP films exhibited high mechanical strength, barrier properties, blocking effect against destructive radiation, biodegradability properties, and potential food packaging applications [70].

4.2 Energy

Recent advancement in biodegradable nanomaterials has led to the development of energy-efficient devices including ignition engines, solar cells, supercapacitors, and rechargeable batteries. Current applications of biodegradable polymers in energy-efficient devices are discussed below.

Ettefaghi *et al*. investigated the biodegradable carbon-based quantum dots as alternatives for metal and metal oxide fuel additives [71]. The use of a combination of diesel-biodiesel-water-biodegradable carbon nanoparticles showed an increase in engine torque and power and a decrease in brake-specific fuel consumption. The bio-nano emulsion fuels also reduced the emission of nitrogen oxide and unburned hydrocarbons [71]. Abdalkarim and coworkers prepared biodegradable dipole responsive magnetic/solar-driven PCF composites reinforced with magnetic cellulose nanocrystals hybrids (MCNC) [72]. The PCF/MCNC composites showed enhanced latent heat phase change enthalpies, thermal stability, and increased magnetic/solar-driven thermal energy storage efficiencies. The authors also reported the potential of PCF/MCNC composites for drying and preservation of agriculture products, including fruits [72].

Shaheen *et al*. synthesized nanocomposites of molybdenum and zinc oxide [MoO_3@ZnO] via chemosynthetic and biomimetic routes and showed a direct bandgap of 4.5 and 3.5 eV, respectively [73]. They demonstrated the semi-conducting and capacitive properties of the biogenic nanocomposite using electrochemical studies included cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) suitable for applications in solar cells [73]. Aziz and coworkers fabricated a methylcellulose: dextran (MC: Dex) polymer blend-based electrolyte system with ammonium iodide (NH_4I) salt for electrical double-layer capacitor (EDLC) application [74]. The electrolyte system was ionic in nature and showed the maximum ionic conductivity as 1.12×10^{-3} S/cm with an electrochemical stability window of 1.27 V. The EDLC device offered an initial specific capacitance of 79 F/g, an energy density of 8.81 Wh/kg and power density of 1111.0 W/kg at a current density of 0.2 mA/cm^2 [74]. Youssef *et al*. prepared the conducting bionanocomposite hydrogels using chitosan (CS)/hydroxyl ethylcellulose (HEC)/polyaniline (PAni) loaded with graphene oxide (GO) doped by silver (Ag) nanoparticles as a semiconductor material for electrical storage devices [75]. CS/HEC/PAni/GO@Ag bionanocomposite hydrogels exhibited improved swelling percentage, capacitance, permittivity, antibacterial activities, and biodegradation properties. The bionanocomposite displayed the highest dc-conductivity of 8.53×10^{-2} S/cm [75].

4.3 Environmental remediation

The rapid industrialization and urbanization across the globe have significantly impacted the terrestrial and aquatic environments by releasing harmful industrial effluents, including colored organic dyes, heavy metals, polycyclic aromatic hydrocarbons (PHAs), chlorinated organics and perfluorosurfactants [76]. The release of these toxic substances imposes serious health concerns on all living beings. Biodegradable nanomaterials have recently been considered highly efficient agents for environmental remediation due to their high chemical reactivity, surface properties, catalytic activity, easy synthesis and fabrication, and environmental benignity. This section covers the applications of biodegradable nanoparticles in environmental remediation.

Rajeswari *et al*. reported the synthesis of biodegradable mixed matrix membranes (MMMs) using aluminum oxide (Al_2O_3) and nano zerovalent iron (nZVI) nanoparticles blended cellulose acetate-polysulfone (CA-PSF) for the removal of methylene blue (MB) dye and Cu (II) metal ions [77]. The authors reported the rejection values 91 and 94% for MB dye and for Cu (II) the rejection values of 84 and 88% using CA-PSF/Al_2O_3 and CA-PSF/nZVI membranes [77]. Pandey and coworkers fabricated slow-release microencapsulated zerovalent iron nanoparticles (ZVINPs) in polylactic acid (PLA)-based microparticles for in-situ groundwater remediation of hydrophilic (methyl orange dye) and hydrophobic (trichloroethylene) water contaminants by electrospraying technique [78]. The authors reported that approximately 8 wt% ZVINPs were slowly released from the biodegradable microparticles after 60 h and 32 h incubation to fully remediate methyl orange (25 mg/L) and trichloroethylene (0.2 vol%) from water, respectively [78]. The photocatalytic properties of Mg-doped ZnO nano-semiconductors for the decontamination of non-treated laundry wastewater were investigated by Oliveira *et al.* [79]. The authors showed the degrading of approximately 53% of pollutants after 240 min of UV–vis irradiation, reducing 31% in total organic carbon (TOC). The treated laundry wastewater promoted the growth of cucumber seeds and tomato roots [79].

Electrospun and thermally cross-linked poly(vinyl alcohol) (PVA) and konjac glucomannan (KGM)-based biodegradable nanofiber membranes loaded with zinc oxide (ZnO) nanoparticles were prepared by Lv *et al*. [80]. ZnO@PVA/KGM membranes exhibited photocatalytic decolorization of methyl orange dye (20 mg L − 1) with a removal efficiency of over 98% under 120 min of solar irradiation. They also investigated efficient air-filtration and antibacterial performances for the ZnO@PVA/KGM membranes [80]. **Figure 2(A)–(D)** shows the schematic presentation of the preparation of the ZnO@PVA/KGM membranes by electrospinning, air filtration process, Photocatalytic degradation, and (D) antibacterial activity of the membranes [80]. Barbosa and coworkers prepared the biodegradable poly(butylene adipate-co-terephthalate) membranes functionalized with cellulose nanoparticles

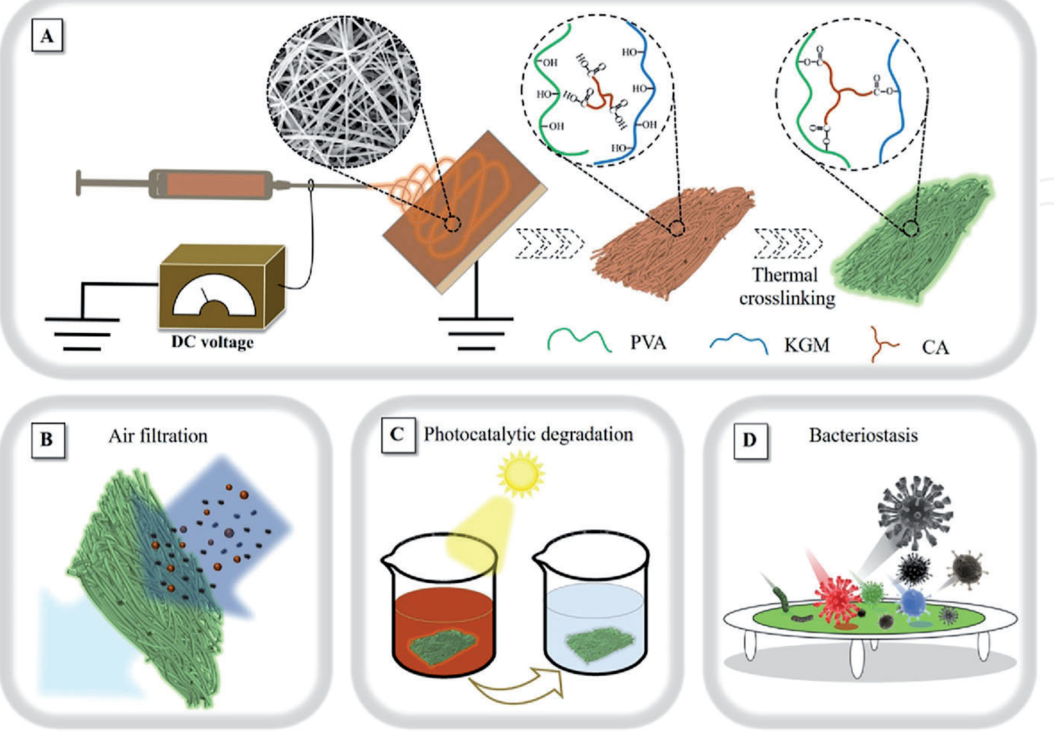

Figure 2.
Schematic representation of the (A) preparation, (B) air filtration process, (C) photocatalytic degradation, and (D) antibacterial activity of the biodegradable ZnO@PVA/KGM nanofiber membranes [80].

(CNS) via phase inversion technique for the removal of chromium (Cr) ions from contaminated drinking water [81]. The CNS functionalized membranes that were subjected to phosphorylation (CNS-P) displayed the removal of 93% and 88% of Cr(VI) and Cr(III), respectively, showing their application in domestic houses and water treatment stations [81].

4.4 Nanomedicine

Biodegradable nanomaterials have been recently investigated in nanomedicine due to their controlled drug release and targeted drug delivery, giving enhanced therapeutic effects and reduced side effects. Biodegradable nanomaterials impose less cytotoxicity on cells. Due to modifying and functionalizing ability, the biodegradable nanoparticles can also improve drug stability and solubility. The vital applications of biodegradable nanoparticles in nanomedicine include drug delivery, cancer therapy, imaging, and antimicrobial activity.

Far *et al*. synthesized biodegradable poly(lactic-co-glycolic acid) (PLGA) nanoparticles (NPs) loaded with mometasone furoate (MF) using the nanoprecipitation method [82]. They reported the controlled release of MF using PLGA NPs over 7 days in vitro with an initial burst release, demonstrating therapeutic potential in nasal delivery applications [82]. Gai and coworkers developed a drug delivery system (DDS) for rheumatoid arthritis (RA) therapy using benzoylaconitine (BAC) encapsulated methoxy-poly (ethylene glycol)-poly(lactide-co-glycolide) (mPEG-PLGA) nanoparticles (NPs) via hydrophobic interaction [83]. The mPEG-PLGA NPs (NP/BAC) system exhibited low cytotoxicity and good biocompatibility for lipopolysaccharide (LPS)-activated macrophages and efficient in vivo anti-inflammatory effect with the high ear (69.8%) and paw (87.1%) swelling suppressing rate. The authors mentioned the possible application of biodegradable NP/BAC system in anti-inflammation and RA therapy as an effective DDS [83].

Qin *et al*. reported the synthesis of tumor-sensitive biodegradable nanoparticles using fluorescent zeolitic imidazolate framework-8 nanoparticles loaded with doxorubicin (FZIF-8/DOX) as the core and a molecularly imprinted polymer (MIP) as the shell (FZIF-8/DOX-MIPs) [84]. FZIF-8/DOX-MIPs showed an inhibitory effect on the growth of MCF-7 tumors and served as a diagnostic agent giving stronger red fluorescence at the tumor sites [84]. A pH-sensitive biodegradable garcinol (GAR)-loaded poly (lactic–co–glycolic acid) (PLGA) coated with Eudragit® S100 (ES100) (GAR-PLGA-ES100 nanoparticles (NPs)) was designed for reducing inflammation caused by pro-inflammatory cytokines in the gastrointestinal tract [85], see **Figure 3**. The authors reported the site-directed release of the drug specifically from NPs at the colonic pH of 7.4, reducing the activation of inflammation that leads to inflammatory bowel disease (IBD) [85].

Han *et al*. developed hypericin encapsulated methoxy poly(ethylene glycol)-b-poly(ε-caprolactone) (PEG-PCL) biodegradable nanoparticles (Hyp-NP) with necrosis affinity and fluorescence imaging in vitro and in vivo [86]. The authors showed the cellular internalization with intracellular cytoplasmic localization and preserved fluorescence and necrosis affinity for Hyp-NPs, suggesting their potential applications in tumor imaging and therapy [86]. Fernández-Gutiérrez and coworkers reported the fabrication of a biocomposite polymeric system for the antibacterial coating of polypropylene mesh materials for hernia repair [87]. **Figure 4(a)–(d)** shows the microscopic and scanning electron microscopic (SEM) images of the meshes with different coatings. The antibacterial coating was performed by a film of chitosan containing poly(D,L-lactide-co-glycolide) (PLGA) nanoparticles loaded with antibiotic (rifampicin) or an antiseptic (chlorhexidine). Both biocomposite coatings exhibited antibacterial activity and cell compatibility, offering a potential strategy to protect meshes from bacterial adhesion following implantation [87].

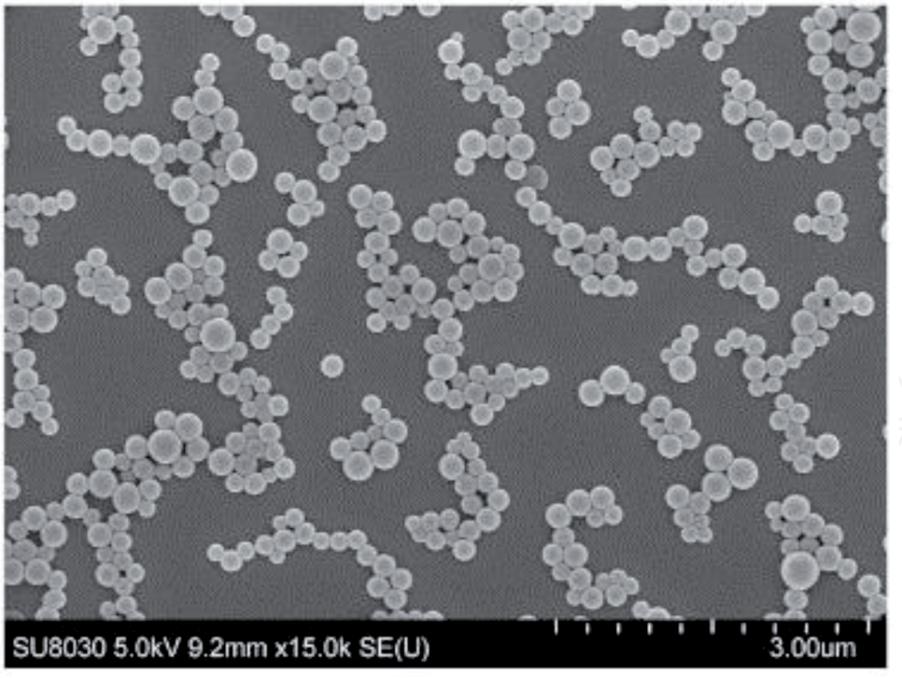

Figure 3.
SEM image of the biodegradable GAR-PLGA-ES100 NPs (At scale 3.00 μm) [85].

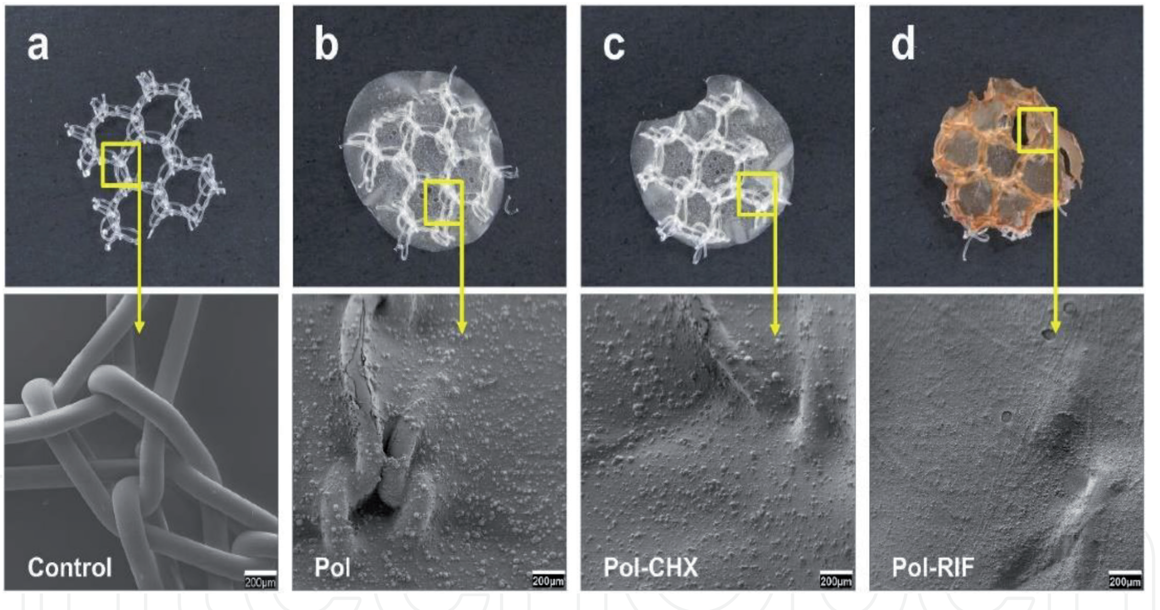

Figure 4.
Macroscopic pictures and SEM micrographs of different meshes (a) nude control (chitosan only), (b) coated with the unloaded biocomposite (chitosan-PLGA), (c) coated with chlorhexidine (CHX)-loaded biocomposite (chitosan-PLGA-CHX), and (d) coated with the rifampicin (RIF)-loaded biocomposite (chitosan-PLG-RIF) [87].

5. Conclusions

Biodegradation is the naturally occurring degradation of complex substances into simple eco-friendly products by the action of microorganisms and plays an imperative role in sustainable development. One of the significant challenges of biodegradation includes the incomplete breakdown of materials due to the complexity of the materials arising from structure, molecular weight, crosslinking, shape, texture, and surface properties. Other setbacks include the screening and identifying of suitable microbes, nutrients, and environmental conditions.

Nanotechnology integrated biodegradation process has recently become an eco-friendly and cost-effective method of diminishing environmental pollutants due to the synergetic effects. The factors including the type of nanomaterials, type of the microorganism, and culture medium directly affect the involvement of nanomaterials in biodegradation. Common types of nanomaterials utilized in biodegradation processes include zero valent metals, oxides, sulfides, nanocomposites, nanoclay, carbon materials, biopolymers, and nanofibers. Biodegradable nanomaterials have been widely applied in food packaging, energy, environmental remediation and nanomedicine.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Danushika C. Manatunga[1]*, Rohan S. Dassanayake[1] and Renuka N. Liyanage[2]

1 Department of Biosystems Technology, Faculty of Technology, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

2 Department of Materials and Mechanical Technology, Faculty of Technology, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

*Address all correspondence to: danushi@sjp.ac.lk; danushi@15gmail.com

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