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Novel Acumens into Biodegradation: Impact of Nanomaterials and Their Contribution

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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- <i>Pseudomonas aeruginosa</i>	Synthesis of ZrO ₂ via <i>P. aeruginosa</i> 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 ₃ O ₄)	Microorganism mediated- <i>Microbacterium</i> sp., <i>Pseudomonas putida</i> and <i>Bacterium</i> Te68R	Enhance the consortium growth that involve in Low-Density Polyethylene (LDPE) degradation	[45]
V. Cadmium Zinc sulfide quantum dots (CdZnS QDs)	Microorganism mediated- <i>Escherichia coli</i>	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- <i>Pseudomonas</i> spp., <i>Sphingomonas</i> spp., <i>Flavobacterium</i> spp., <i>Burkholderia</i> spp., <i>Rhodococcus</i> spp., <i>Mycobacterium</i> spp., and <i>Bacillus</i> 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- <i>Arthrobacter globiformis</i> D47	Bacteria decorated nanocellulose being used as a scaffold to grow the bacteria as well as to remove Diuron via biodegradation	[48]
II. Fe ₃ O ₄ /biochar composites	Microorganism mediated- <i>R. capsulatus</i>	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- <i>Pseudomonas putida</i> strain MK4 (DQ318885), <i>Bacterium</i> Te68R strain PN12 (DQ423487), <i>P. aeruginosa</i> strain PS1 (EU741797), <i>P. putida</i> strain PW1 (EU741798), and <i>P. aeruginosa</i> 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- <i>S. cerevisiae</i> , Actinomycetes	Immobilization of microbes for bioremediation of heavy metals	[51]
Biopolymer based nanomaterials			
I. Alginate beads	Microorganism mediated- <i>Acinetobacter sp.</i> , <i>Bacillus circulans</i> , <i>Bacillus licheniformis</i> , <i>Brevibacillus brevis</i> , <i>Burkholderia cepacia</i> , <i>Leifsonia aquatica</i> and <i>Sphingomonas paucimobilis</i>	Improved the bacterial attachment required for oil bioremediation	[52]
II. Chitosan beads	Microorganism mediated- <i>Serratia sp. AC-11</i>	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- <i>Pseudomonas aeruginosa ATCC 47085</i>	Provide suitable platforms for preservation of living bacterial cells and direct use for bioremediation of methylene blue	[54]
II. Cyclodextrin nanofibers	Microorganism mediated- <i>Lysinibacillus sp. NOSK</i>	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. Polycaprolactone (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.

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 [$\text{MoO}_3@\text{ZnO}$] 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 $1.12 \times 10^{-3} \text{ S/cm}$ 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 $8.53 \times 10^{-2} \text{ S/cm}$ [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.

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References

- [1] Mensah J. Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent Soc Sci* [Internet]. 2019; 5(1). Available from: <https://doi.org/10.1080/23311886.2019.1653531>
- [2] Tahri N, Bahafid W, Sayel H, El Ghachtouli N. Biodegradation: Involved Microorganisms and Genetically Engineered Microorganisms. In: *Biodegradation - Life of Science* [Internet]. 2013. p. 289-320. Available from: <https://www.intechopen.com/books/biodegradation-life-of-science/biodegradation-involved-microorganisms-and-genetically-engineered-microorganisms>
- [3] Verma R, Vinoda KS, Papireddy M, Gowda ANS. Toxic Pollutants from Plastic Waste- A Review. *Procedia Environ Sci* [Internet]. 2016;35:701-8. Available from: <http://dx.doi.org/10.1016/j.proenv.2016.07.069>
- [4] Huang Y, Xiao L, Li F, Xiao M, Lin D, Long X, et al. Microbial degradation of pesticide residues and an emphasis on the degradation of cypermethrin and 3-phenoxy benzoic acid: A review. *Molecules*. 2018;23(9).
- [5] Antipova T V., Zhelifonova VP, Zaitsev K V., Nedorezova PM, Aladyshev AM, Klyamkina AN, et al. Biodegradation of Poly- ϵ -caprolactones and Poly-l-lactides by Fungi. *J Polym Environ*. 2018;26(12):4350–9.
- [6] Jawed K, Yazdani SS, Koffas MA. Advances in the development and application of microbial consortia for metabolic engineering. *Metab Eng Commun* [Internet]. 2019;9(November 2018):e00095. Available from: <https://doi.org/10.1016/j.mec.2019.e00095>
- [7] Sahoo NK, Pakshirajan K, Ghosh PK, Ghosh A. Biodegradation of 4-chlorophenol by *Arthrobacter chlorophenolicus* A6: Effect of culture conditions and degradation kinetics. *Biodegradation*. 2011;22(2):275-86.
- [8] Brzeszcz J, Kaszycki P. Aerobic bacteria degrading both n-alkanes and aromatic hydrocarbons: an undervalued strategy for metabolic diversity and flexibility. *Biodegradation* [Internet]. 2018;29(4):359-407. Available from: <https://doi.org/10.1007/s10532-018-9837-x>
- [9] Singh B, Singh K. Microbial degradation of herbicides. *Crit Rev Microbiol*. 2016;42(2):245-61.
- [10] Gogada R, Singh SS, Lunavat SK, Pamarthi MM, Rodrigue A, Vadivelu B, et al. Engineered *Deinococcus radiodurans* R1 with NiCoT genes for bioremoval of trace cobalt from spent decontamination solutions of nuclear power reactors. *Appl Microbiol Biotechnol*. 2015;99(21): 9203-13.
- [11] N.Karak. Biodegradable polymers. *Vegetable Oil-Based Polymers*. 2012. 31-53 p.
- [12] Vázquez-Núñez E, Molina-Guerrero CE, Peña-Castro JM, Fernández-Luqueño F, de la Rosa-Álvarez MG. Use of nanotechnology for the bioremediation of contaminants: A review. *Processes*. 2020;8(7):1-17.
- [13] Mandeep, Shukla P. Microbial Nanotechnology for Bioremediation of Industrial Wastewater. *Front Microbiol*. 2020;11(November):1-8.
- [14] Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Front Microbiol*. 2017;8(JUN):1-13.

- [15] Fakruddin M, Hossain Z, Afroz H. Prospects and applications of nanobiotechnology: A medical perspective. *J Nanobiotechnology*. 2012;10:1-8.
- [16] Mathew J, Joy J, George SC. Potential applications of nanotechnology in transportation: A review. *J King Saud Univ - Sci* [Internet]. 2019;31(4):586-94. Available from: <https://doi.org/10.1016/j.jksus.2018.03.015>
- [17] Subramanian V, Lee T. Nanotechnology-based flexible electronics. *Nanotechnology*. 2012;23(34):12-4.
- [18] Nile SH, Baskar V, Selvaraj D, Nile A, Xiao J, Kai G. Nanotechnologies in Food Science: Applications, Recent Trends, and Future Perspectives [Internet]. Vol. 12, Nano-Micro Letters. Springer Singapore; 2020. 1-34 p. Available from: <https://doi.org/10.1007/s40820-020-0383-9>
- [19] S. Dassanayake R, Acharya S, Abidi N. Biopolymer-Based Materials from Polysaccharides: Properties, Processing, Characterization and Sorption Applications. In: *Advanced Sorption Process Applications* [Internet]. 2019. p. 1-24. Available from: <https://www.intechopen.com/books/advanced-sorption-process-applications/biopolymer-based-materials-from-polysaccharides-properties-processing-characterization-and-sorption->
- [20] Fernando MS, De Silva RM, De Silva KMN. Synthesis, characterization, and application of nano hydroxyapatite and nanocomposite of hydroxyapatite with granular activated carbon for the removal of Pb 2+ from aqueous solutions. *Appl Surf Sci* [Internet]. 2015;351(January 2020):95-103. Available from: <http://dx.doi.org/10.1016/j.apsusc.2015.05.092>
- [21] A. K. D. Veromee Kalpana Wimalasiri, M. Shanika Fernando, Karolina Dziemidowicz, Gareth R. Williams, K. Rasika Koswattage, D. P. Dissanayake, K. M. Nalin de Silva and RM de S. Structure–Activity Relationship of Lanthanide-Incorporated. *ACS Omega*. 2021;6(21):13527-43.
- [22] Wimalasiri AKDVK, Fernando MS, Williams GR, Dissanayake DP, de Silva KMN, de Silva RM. Microwave assisted accelerated fluoride adsorption by porous nanohydroxyapatite. *Mater Chem Phys* [Internet]. 2021;257(July 2019):123712. Available from: <https://doi.org/10.1016/j.matchemphys.2020.123712>
- [23] Manatunga DC, de Silva RM, Nalin De Silva KM, de Silva N, Premalal EVA. Metal and polymer-mediated synthesis of porous crystalline hydroxyapatite nanocomposites for environmental remediation. *R Soc Open Sci*. 2018;5(1).
- [24] Fernando MS, Wimalasiri AKDVK, Ratnayake SP, Jayasinghe JMARB, William GR, Dissanayake DP, et al. Improved nanocomposite of montmorillonite and hydroxyapatite for defluoridation of water. *RSC Adv*. 2019;9(61):35588-98.
- [25] Fernando MS, Wimalasiri AKDVK, Dziemidowicz K, Williams GR, Koswattage KR, Dissanayake DP, et al. Biopolymer-Based Nanohydroxyapatite Composites for the Removal of Fluoride, Lead, Cadmium, and Arsenic from Water. *ACS Omega*. 2021;6(12):8517-30.
- [26] Ionescu AM. Nanotechnology and Global Security. *Connect QJ*. 2016;15(2):31-47.
- [27] Su S, Kang PM. Systemic review of biodegradable nanomaterials in nanomedicine. *Nanomaterials*. 2020;10(4).
- [28] Dhillon GS, Kaur S, Verma M, Brar SK. Biopolymer-based

nanomaterials: Potential applications in bioremediation of contaminated wastewaters and soils [Internet]. 1st ed. Vol. 59, Comprehensive Analytical Chemistry. Elsevier B.V.; 2012. 91-129 p. Available from: <http://dx.doi.org/10.1016/B978-0-444-56328-6.00003-7>

[29] Pathak VM, Navneet Kumar. Implications of SiO₂ nanoparticles for in vitro biodegradation of low-density polyethylene with potential isolates of *Bacillus*, *Pseudomonas*, and their synergistic effect on *Vigna mungo* growth. *Energy, Ecol Environ*. 2017;2(6):418-27.

[30] Bhatia M, Girdhar A, Chandrakar B, Tiwari A. Implicating nanoparticles as potential biodegradation enhancers: A review. *J Nanomedicine Nanotechnol*. 2013;4(4).

[31] Rgpv B, Rgpv B, Rgpv B. Ldpe-Biodegradation Using Microbial Consortium By the Incorporation of Cobalt Ferrite Nanoparticle As the Enhancer for Biodegradation. *Int J Adv Eng Res Dev*. 2017;4(06):794-800.

[32] Misson M, Zhang H, Jin B. Nanobiocatalyst advancements and bioprocessing applications. *J R Soc Interface*. 2015;12(102):1-20.

[33] Koedrith P, Thasiphu T, Weon J Il, Boonprasert R, Tuitemwong K, Tuitemwong P. Recent trends in rapid environmental monitoring of pathogens and toxicants: Potential of nanoparticle-based biosensor and applications. *Sci World J*. 2015;2015:1-12.

[34] Li X, Xu H, Chen ZS, Chen G. Biosynthesis of nanoparticles by microorganisms and their applications. *J Nanomater*. 2011;2011:1-16.

[35] Das RK, Pachapur VL, Lonappan L, Naghdi M, Pulicharla R, Maiti S, et al. Biological synthesis of metallic nanoparticles: plants, animals and

microbial aspects. *Nanotechnol Environ Eng*. 2017;2(1):1-21.

[36] Albanese A, Tang PS, Chan WCW. The effect of nanoparticle size, shape, and surface chemistry on biological systems. *Annu Rev Biomed Eng*. 2012;14:1-16.

[37] Khan I, Saeed K, Khan I. Nanoparticles: Properties, applications and toxicities. *Arab J Chem* [Internet]. 2019;12(7):908-31. Available from: <https://doi.org/10.1016/j.arabjc.2017.05.011>

[38] Singh M, Mitra CK, Morve RK. Rizwan, 2014. *J Nanoparticles*. 2014;2014(2):740-57.

[39] Shrivastava K, Shankar R, Dewangan K. Gold nanoparticles as a localized surface plasmon resonance based chemical sensor for on-site colorimetric detection of arsenic in water samples. *Sensors Actuators, B Chem* [Internet]. 2015;220:1376-83. Available from: <http://dx.doi.org/10.1016/j.snb.2015.07.058>

[40] Alzahrani E. Colorimetric Detection Based on Localized Surface Plasmon Resonance Optical Characteristics for Sensing of Mercury Using Green-Synthesized Silver Nanoparticles. *J Anal Methods Chem*. 2020;2020:1-14.

[41] M. T. Amin, A. A. Alazba and UMA. A Review of Removal of Pollutants from Water/Wastewater Using Different Types of Nanomaterials. *Adv Mater Sci Eng*. 2014;2014:1-24.

[42] Dong H, Li L, Lu Y, Cheng Y, Wang Y, Ning Q, et al. Integration of nanoscale zero-valent iron and functional anaerobic bacteria for groundwater remediation: A review. *Environ Int* [Internet]. 2019;124(December 2018):265-77. Available from: <https://doi.org/10.1016/j.envint.2019.01.030>

[43] Debnath B, Majumdar M, Bhowmik M, Bhowmik KL, Debnath A,

- Roy DN. The effective adsorption of tetracycline onto zirconia nanoparticles synthesized by novel microbial green technology. *J Environ Manage* [Internet]. 2020;261(September 2019):1-13. Available from: <https://doi.org/10.1016/j.jenvman.2020.110235>
- [44] Mohanraj R, Gnanamangai BM, Poornima S, Oviyaa V, Ramesh K, Vijayalakshmi G, et al. Decolourisation efficiency of immobilized silica nanoparticles synthesized by actinomycetes. *Mater Today Proc* [Internet]. 2020;(In press). Available from: <https://doi.org/10.1016/j.matpr.2020.04.139>
- [45] Kapri A, Zaidi MGH, Satlewal A, Goel R. SPION-accelerated biodegradation of low-density polyethylene by indigenous microbial consortium. *Int Biodeterior Biodegrad* [Internet]. 2010;64(3):238-44. Available from: <http://dx.doi.org/10.1016/j.ibiod.2010.02.002>
- [46] Wang X, Pu J, Liu Y, Ba F, Cui M, Li K, et al. Immobilization of functional nano-objects in living engineered bacterial biofilms for catalytic applications. *Natl Sci Rev*. 2019;6(5):929-43.
- [47] Biswas B, Sarkar B, Rusmin R, Naidu R. Bioremediation of PAHs and VOCs: Advances in clay mineral-microbial interaction. *Environ Int* [Internet]. 2015;85:168-81. Available from: <http://dx.doi.org/10.1016/j.envint.2015.09.017>
- [48] Liu J, Morales-Narváez E, Vicent T, Merkoçi A, Zhong GH. Microorganism-decorated nanocellulose for efficient diuron removal. *Chem Eng J* [Internet]. 2018;354:1083-91. Available from: <https://doi.org/10.1016/j.cej.2018.08.035>
- [49] He S, Zhong L, Duan J, Feng Y, Yang B, Yang L. Bioremediation of wastewater by iron Oxide-Biochar nanocomposites loaded with photosynthetic bacteria. *Front Microbiol*. 2017;8(MAY):1-10.
- [50] Sah A, Kapri A, Zaidi MGH, Negi H, Goel R. Implications of fullerene-60 upon in-vitro LDPE biodegradation. *J Microbiol Biotechnol*. 2010;20(5):908-16.
- [51] Fosso-Kankeu E, Mulaba-Bafubiandi AF, Mishra AK. Prospects for Immobilization of Microbial Sorbents on Carbon Nanotubes for Biosorption: Bioremediation of Heavy Metals Polluted Water. *Appl Nanotechnol Water Res*. 2014;9781118496(January 2018):37-61.
- [52] Zommere Ž, Nikolajeva V. Immobilization of bacterial association in alginate beads for bioremediation of oil-contaminated lands. *Environ Exp Biol*. 2017;15(January):105-11.
- [53] Garcia ACFS, Araújo BR, Birolli WG, Marques CG, Diniz LEC, Barbosa AM, et al. Fluoranthene Biodegradation by *Serratia* sp. AC-11 Immobilized into Chitosan Beads. *Appl Biochem Biotechnol*. 2019;188(4):1168-84.
- [54] Sarioglu OF, Keskin NOS, Celebioglu A, Tekinay T, Uyar T. Bacteria encapsulated electrospun nanofibrous webs for remediation of methylene blue dye in water. *Colloids Surfaces B Biointerfaces* [Internet]. 2017;152:245-51. Available from: <http://dx.doi.org/10.1016/j.colsurfb.2017.01.034>
- [55] San Keskin NO, Celebioglu A, Sarioglu OF, Uyar T, Tekinay T. Encapsulation of living bacteria in electrospun cyclodextrin ultrathin fibers for bioremediation of heavy metals and reactive dye from wastewater. *Colloids Surfaces B Biointerfaces* [Internet]. 2018;161:169-76. Available from: <http://dx.doi.org/10.1016/j.colsurfb.2017.10.047>

- [56] Cai Y, Xu Z, Shuai Q, Zhu F, Xu J, Gao X, et al. Tumor-targeting peptide functionalized PEG-PLA micelles for efficient drug delivery. *Biomater Sci*. 2020;8(8):2274-82.
- [57] Wang M, Zhan J, Xu L, Wang Y, Lu D, Li Z, et al. Synthesis and characterization of PLGA-PEG-PLGA based thermosensitive polyurethane micelles for potential drug delivery. *J Biomater Sci Polym Ed*. 2020;32(5):613-34.
- [58] Łukasiewicz S, Mikołajczyk A, Błasiak E, Fic E, Dziedzicka-Wasylewska M. Polycaprolactone Nanoparticles as Promising Candidates for Nanocarriers in Novel Nanomedicines. *Pharmaceutics*. 2021;13(2):191.
- [59] Unnati Garg, Swati Chauhan, Upendra Nagaich NJ. Current Advances in Chitosan Nanoparticles Based Drug Delivery and Targeting. *Adv Pharm Bull [Internet]*. 2019;9(2):195-204. Available from: <http://dx.doi.org/10.15171/jcvtr.2015.24>
- [60] Mandal AK. Dendrimers in targeted drug delivery applications: a review of diseases and cancer. *Int J Polym Mater Polym Biomater [Internet]*. 2021;70(4):287-97. Available from: <https://doi.org/10.1080/00914037.2020.1713780>
- [61] Beltrán-Gracia E, López-Camacho A, Higuera-Ciajara I, Velázquez-Fernández JB, Vallejo-Cardona AA. Nanomedicine review: Clinical developments in liposomal applications [Internet]. Vol. 10, *Cancer Nanotechnology*. Springer Vienna; 2019. 1-40 p. Available from: <https://doi.org/10.1186/s12645-019-0055-y>
- [62] Patel A, Enman J, Gulkova A, Guntoro PI, Dutkiewicz A, Ghorbani Y, et al. Integrating biometallurgical recovery of metals with biogenic synthesis of nanoparticles. *Chemosphere*. 2021;263:1-23.
- [63] Mahapatro A, Singh DK. Biodegradable nanoparticles are excellent vehicle for site directed in-vivo delivery of drugs and vaccines. *J Nanobiotechnology [Internet]*. 2011;9(1):55. Available from: <http://www.jnanobiotechnology.com/content/9/1/55>
- [64] Jacob J, Lawal U, Thomas S, Valapa RB. Biobased polymer composite from poly(lactic acid): processing, fabrication, and characterization for food packaging [Internet]. *Processing and Development of Polysaccharide-Based Biopolymers for Packaging Applications*. Elsevier Inc.; 2020. 97-115 p. Available from: <http://dx.doi.org/10.1016/B978-0-12-818795-1.00004-6>
- [65] Pandey VK, Upadhyay SN, Niranjana K, Mishra PK. Antimicrobial biodegradable chitosan-based composite Nano-layers for food packaging. *Int J Biol Macromol [Internet]*. 2020;157:212-9. Available from: <https://doi.org/10.1016/j.ijbiomac.2020.04.149>
- [66] Sreelekha Ediyilyam, Bini George, Sarojini Sharath Shankar, Thomas Thuruthiyil Dennis Stanisław Wacławek, Mirosław Ćerník and VVTP. Chitosan / Gelatin / Silver Nanoparticles Composites Films for Biodegradable Food Packaging Applications. *Polymers (Basel)*. 2021;13(1680):1-18.
- [67] Kumar S, Mudai A, Roy B, Basumatary IB, Mukherjee A, Dutta J. Biodegradable hybrid nanocomposite of chitosan/gelatin and green synthesized zinc oxide nanoparticles for food packaging. *Foods*. 2020;9(1143):1-13.
- [68] K. SS, Indumathi MP, Rajarajeswari GR. Mahua oil-based polyurethane/chitosan/nano ZnO composite films for biodegradable food packaging applications. *Int J Biol*

- Macromol [Internet]. 2019;124:163-74. Available from: <https://doi.org/10.1016/j.ijbiomac.2018.11.195>
- [69] Peighambardoust SJ, Peighambardoust SH, Mohammadzadeh Pournasir N, Pakdel P. Properties of active starch-based films incorporating a combination of Ag, ZnO and CuO nanoparticles for potential use in food packaging applications. Food Packag Shelf Life [Internet]. 2019;22(October):100420. Available from: <https://doi.org/10.1016/j.fpsl.2019.100420>
- [70] Mahmoodi A, Ghodrati S, Khorasani M. High-Strength, Low-Permeable, and Light-Protective Nanocomposite Films Based on a Hybrid Nanopigment and Biodegradable PLA for Food Packaging Applications. ACS Omega. 2019;4(12):14947-54.
- [71] Etefaghi E, Ghobadian B, Rashidi A, Najafi G, Khoshtaghaza MH, Rashtchi M, et al. A novel bio-nano emulsion fuel based on biodegradable nanoparticles to improve diesel engines performance and reduce exhaust emissions. Renew Energy [Internet]. 2018;125:64-72. Available from: <https://doi.org/10.1016/j.renene.2018.01.086>
- [72] Abdalkarim SYH, Ouyang Z, Yu HY, Li Y, Wang C, Asad RAM, et al. Magnetic cellulose nanocrystals hybrids reinforced phase change fiber composites with highly thermal energy storage efficiencies. Carbohydr Polym [Internet]. 2021;254(December 2020):117481. Available from: <https://doi.org/10.1016/j.carbpol.2020.117481>
- [73] Shaheen I, Ahmad KS, Jaffri SB, Ali D. Biomimetic [MoO₃@ZnO] semiconducting nanocomposites: Chemo-proportional fabrication, characterization and energy storage potential exploration. Renew Energy [Internet]. 2021;167:568-79. Available from: <https://doi.org/10.1016/j.renene.2020.11.115>
- [74] Aziz SB, Brza MA, Mishra K, Hamsan MH, Karim WO, Abdullah RM, et al. Fabrication of high performance energy storage EDLC device from proton conducting methylcellulose: Dextran polymer blend electrolytes. J Mater Res Technol [Internet]. 2020;9(2):1137-50. Available from: <https://doi.org/10.1016/j.jmrt.2019.11.042>
- [75] Youssef AM, Hasanin MS, El-Aziz MEA, Turkey GM. Conducting chitosan/hydroxyethyl cellulose/ polyaniline bionanocomposites hydrogel based on graphene oxide doped with Ag-NPs. Int J Biol Macromol [Internet]. 2021;167:1435-44. Available from: <https://doi.org/10.1016/j.ijbiomac.2020.11.097>
- [76] Kalita E, Baruah J. Environmental remediation [Internet]. Colloidal Metal Oxide Nanoparticles. Elsevier Inc.; 2020. 525-576 p. Available from: <http://dx.doi.org/10.1016/B978-0-12-813357-6.00014-0>
- [77] Rajeswari A, Jackcina Stobel Christy E, Ida Celine Mary G, Jayaraj K, Pius A. Cellulose acetate based biopolymeric mixed matrix membranes with various nanoparticles for environmental remediation-A comparative study. J Environ Chem Eng [Internet]. 2019;7(4):103278. Available from: <https://doi.org/10.1016/j.jece.2019.103278>
- [78] Pandey K, Saha S. Microencapsulated Zero Valent Iron NanoParticles in Polylactic acid matrix for in situ remediation of contaminated water. J Environ Chem Eng [Internet]. 2020;8(4):103909. Available from: <https://doi.org/10.1016/j.jece.2020.103909>
- [79] Oliveira AG, Andrade J de L, Montanha MC, Ogawa CYL, de Souza Freitas TKF, Moraes JCG, et al. Wastewater treatment using Mg-doped ZnO nano-semiconductors: A study of

their potential use in environmental remediation. *J Photochem Photobiol A Chem.* 2021 Feb 15;407:113078.

[80] Lv D, Wang R, Tang G, Mou Z, Lei J, Han J, et al. Ecofriendly Electrospun Membranes Loaded with Visible-Light-Responding Nanoparticles for Multifunctional Usages: Highly Efficient Air Filtration, Dye Scavenging, and Bactericidal Activity. *ACS Appl Mater Interfaces.* 2019;11(13):12880-9.

[81] Barbosa RFS, Souza AG, Maltez HF, Rosa DS. Chromium removal from contaminated wastewaters using biodegradable membranes containing cellulose nanostructures. *Chem Eng J [Internet].* 2020;395(January):125055. Available from: <https://doi.org/10.1016/j.cej.2020.125055>

[82] Far J, Abdel-Haq M, Gruber M, Abu Ammar A. Developing Biodegradable Nanoparticles Loaded with Mometasone Furoate for Potential Nasal Drug Delivery. *ACS Omega.* 2020;5(13):7432-9.

[83] Gai W, Hao X, Zhao J, Wang L, Liu J, Jiang H, et al. Delivery of benzoyleconitine using biodegradable nanoparticles to suppress inflammation via regulating NF- κ B signaling. *Colloids Surfaces B Biointerfaces [Internet].* 2020;191(March):110980. Available from: <https://doi.org/10.1016/j.colsurfb.2020.110980>

[84] Qin YT, Feng YS, Ma YJ, He XW, Li WY, Zhang YK, et al. Tumor-Sensitive Biodegradable Nanoparticles of Molecularly Imprinted Polymer-Stabilized Fluorescent Zeolitic Imidazolate Framework-8 for Targeted Imaging and Drug Delivery. *ACS Appl Mater Interfaces.* 2020;12(22):24585-98.

[85] Jacob EM, Borah A, Pillai SC, Kumar DS. Garcinol encapsulated pH-sensitive biodegradable nanoparticles: A novel therapeutic strategy for the treatment of

inflammatory bowel disease. *Polymers (Basel).* 2021;13(6).

[86] Han X, Taratula O, Taratula O, Xu K, St Lorenz A, Moses A, et al. Biodegradable Hypericin-Containing Nanoparticles for Necrosis Targeting and Fluorescence Imaging. *Mol Pharm.* 2020;17(5):1538-45.

[87] Fernández-Gutiérrez M, Pérez-Köhler B, Benito-Martínez S, García-Moreno F, Pascual G, García-Fernández L, et al. Development of biocomposite polymeric systems loaded with antibacterial nanoparticles for the coating of polypropylene biomaterials. *Polymers (Basel).* 2020;12(8).