

# Polyethylene Degradation using Chitosan-Incorporated Iron Nanoparticles: A Review

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**Abstract:** The rapid accumulation of polyethylene (PE) waste has created a major environmental concern, necessitating the development of sustainable degradation strategies, as the polyethylene waste offers resistance to natural degradation. Also, conventional disposal techniques such as landfilling and incineration are related to secondary pollution. This review includes the recent advancements in polyethylene degradation using chitosan-incorporated iron nanoparticles (FeNPs), a hybrid system combining biopolymer functionality with nanocatalytic activity. The synergistic interaction between chitosan and FeNPs enhances reactive oxygen species (ROS) generation, promotes microbial colonization, and improves surface modification of polyethylene, thereby accelerating degradation. This synergistic interaction improves the chemical and microbial degradation pathways as chitosan, a biodegradable biopolymer, acts as a stabilizing matrix, while FeNPs provide catalytic activity. This review highlights the synthetic methods, degradation mechanisms, performance evaluation, and environmental implications while identifying current research gaps and future directions. The review also includes the potential of chitosan-FeNP composites as an eco-friendly and scalable solution for plastic waste remediation with the key challenges for the large-scale application.

**Keywords:** Polyethylene, Chitosan, Iron nanoparticles, Nanocomposites, Biodegradation, ROS, catalytic activity, microbial colonization, chitin

## 1. INTRODUCTION

Polyethylene (PE) is a widely used synthetic polymer due to its durability, low cost, and chemical resistance[1]. It is obtained in two different forms, such as low-density polyethylene (LDPE) and high-density polyethylene (HDPE). However, these properties are leading to the major environmental problem due to its properties such as chemical stability and hydrophobicity/non-polarity, presence of saturated carbon chains that resist microbial attack[2], which in turn contribute to their persistence in the environment, for centuries, thereby causing severe ecological and health impacts. Consequently, PE waste has become a major contributor to plastic pollution, especially in oceans, rivers, and landfills, causing harm to wildlife, ecosystems, and human health[3]. Conventional waste management approaches, such as incineration and landfilling, often result in toxic emissions and secondary pollution such as microplastic leaching[4]. Also, the thermal methods are more energy-intensive process. Hence, to address the [5]. Biological degradation, involving the use of microorganisms or biocatalysts, offers a promising route as an eco-friendly solution. However, inert polyethylene's stable, non-polar structure makes it resistant to microbial attack, posing a challenge for biodegradation[6]. In some cases, biological methods are slow due to the limited microbial access[7].

Recent studies have focused on overcoming this resistance through various methods, including mechanical, chemical, and biological degradation[7]. To enhance the degradation process, researchers have turned to novel approaches that integrate the biological agents with nanoparticles, which can help overcome polyethylene's inherent resistance to breakdown[5]. In recent years, there has been a growing interest in combining biocatalytic agents with nanoparticles to enhance the degradation process[5]. The objective of this review is to analyze synthesis strategies, degradation efficiency, environmental impact, and future potential.

There are several studies for the hybrid approaches combining biological systems with nanotechnology to overcome these limitations[8]. Among these, chitosan-incorporated iron nanoparticles (chitosan-FeNPs) have gained attention due to their ability to integrate biocompatibility, catalytic activity, low toxicity, and environmental

safety[9]. This ecofriendly method is a combination of chemical and biological pathways and is a potential method for controlled and sustained degradation. By combining the stabilizing properties of chitosan with the catalytic power of iron nanoparticles (FeNPs), a new pathway for accelerated degradation has emerged[10]. Chitosan acts as a matrix and stabilizer, preventing FeNP aggregation[11]. FeNPs embedded in chitosan matrix offer controlled reactivity and sustained degradation capacity[10]. It has enhanced mechanical strength, surface reactivity, and bioactivity. Therefore, use of chitosan combined with iron nanoparticles is a promising hybrid system for polyethylene degradation. Research has shown that polyethylene can undergo oxidative degradation through the generation of reactive oxygen species (ROS), such as hydroxyl radicals and superoxide anions, which break the long carbon chains of PE[12, 13].

This review provides a comprehensive integration of biological and nanocatalytic degradation pathways. It highlights the synergistic role of chitosan as a stabilizer and bioenhancer. The structural activity correlations, such as particle size, oxidation state, and polymer interactions. The paper also includes emerging concepts such as photocatalysis, bioaugmentation, circular economy applications. Attempts are made to identify scalability challenges and environmental risk considerations.

### CORE COMPONENTS OF THE HYBRID SYSTEM:

Chitosan is a biocompatible matrix, a nontoxic biopolymer having amine (-NH<sub>2</sub>) and hydroxyl (-OH) functional groups[14]. It is copolymer of d-glucosamine and N-acetyl-d-glucosamine, in which the number of d-glucosamine and N-acetyl-d-glucosamine residues varies depending on the degree of deacetylation of chitin, sourced from crustacean shells[15] (Figure 1). It is a biodegradable biopolymer and has shown promise in various environmental applications, including waste treatment and plastic degradation[16]. It is nontoxic and can act as a catalyst for various chemical reactions[17].

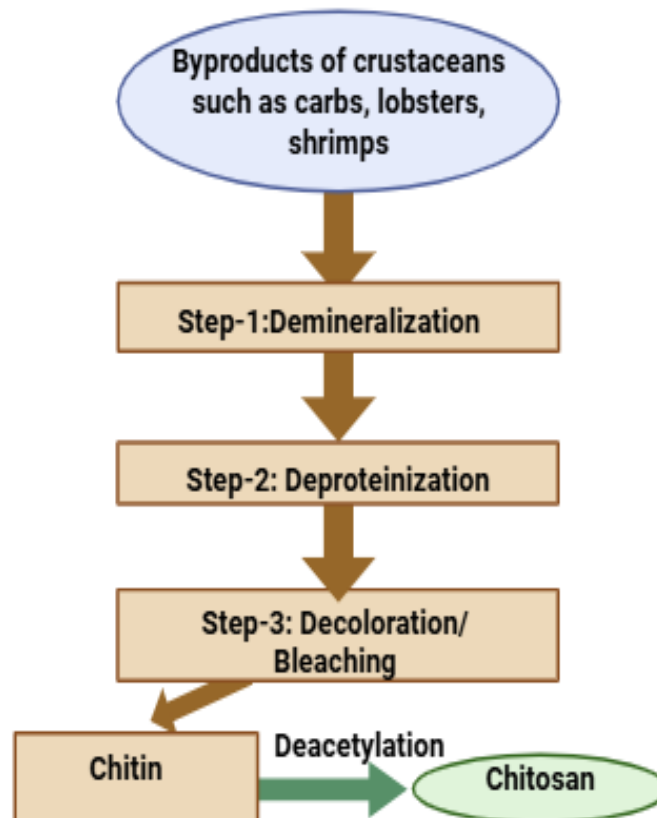


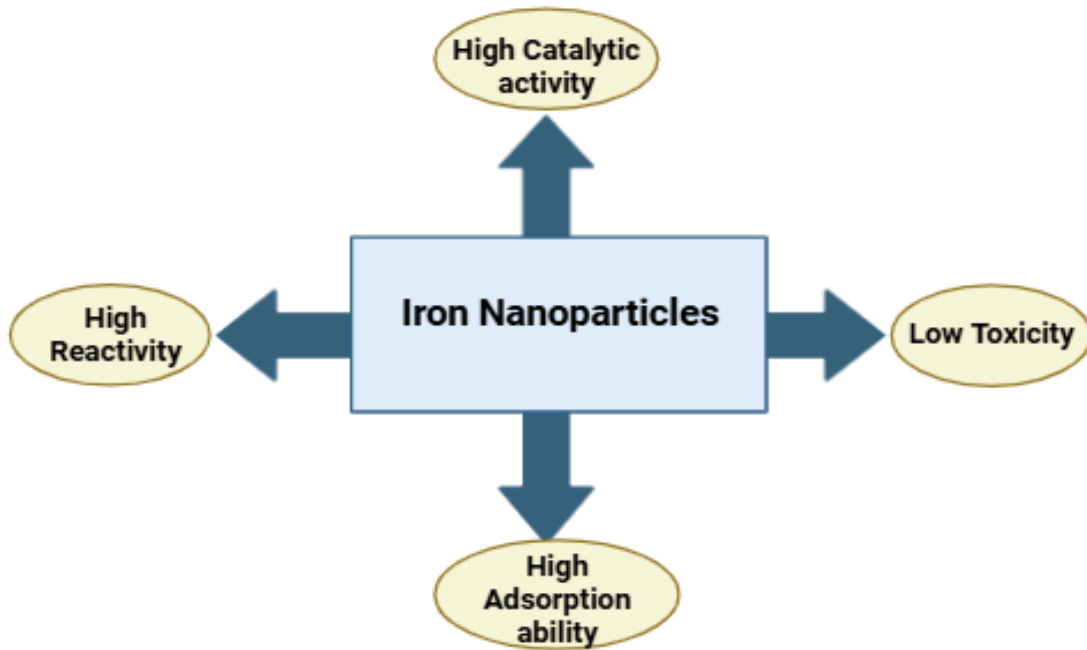
Figure 1. Steps involved in Chitosan formation

Chitosan role in PE degradation is due to its stability, as it prevents FeNPs from clumping, maintaining high catalytic reactivity[13]. It is known for enhancing the bioadhesion characteristics as it makes the hydrophobic PE surface more "attractive" to microbes, facilitating enzymatic attack[18]. Chitosan forms a scaffold, prevents the FeNP aggregation and promotes microbial biofilm formation. Chitosan acts as a chelating agent of metal ions, as the functional groups bind to metal ions, enhancing the overall catalytic efficiency of the composite[19]. Thus, chitosan has dual role in polyethylene degradation: Its biological role enhances microbial colonization and enzymatic activity and its structural role: acts as a matrix to stabilize and disperse FeNPs[13]. Chitosan can improve the surface hydrophilicity of polyethylene further facilitating the microbial attack and enzymatic degradation[20]. Due to its biodegradability, non-toxicity, and abundance, chitosan has gained significant attention in various environmental applications, including waste treatment, wastewater purification, and as a catalyst for polymer degradation[21].

Recent studies have highlighted the role of chitosan in enhancing the microbial degradation of polyethylene. The degradation of polyethylene using chitosan is thought to occur through the production of enzymes, chemical reactions, and a combination of physical and chemical mechanisms[20]. Chitosan can interact with microbial species and may act as a stabilizing agent or a carrier to enhance microbial adhesion to polyethylene surfaces, thus facilitating biodegradation[20]. Chitosan can act as a binding agent, stabilizing iron nanoparticles and facilitating their interaction with polyethylene[22]. Furthermore, its chelation properties allow it to interact with metal ions, enhancing catalytic activities when combined with nanoparticles such as FeNPs[23]. Additionally, it can promote microbial colonization on polyethylene surfaces, thereby improving the biological degradation process[24]. In some cases, chitosan has been shown to enhance the adhesion of microorganisms to polyethylene, increasing the rate of degradation by providing a stable environment for the microorganisms to attach to the plastic surface[24]. The addition of chitosan also increased the number of microbial species involved in PE degradation, leading to higher degradation efficiency.

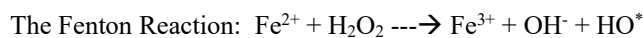
#### **IRON NANOPARTICLES (FENPS) AND THEIR ROLE IN POLYETHYLENE DEGRADATION**

Iron Nanoparticles (FeNPs) exist as zero-valent iron (nZVI) or  $Fe^{2+}/Fe^{3+}$  oxides and are the primary agents for chemical pre-treatment[25]. Iron nanoparticles have been studied for their catalytic properties in the degradation of polyethylene and other organic pollutants[25]. FeNPs are a class of nanomaterials with high surface area-to-volume ratios and enhanced catalytic properties[26]. FeNPs have been investigated for their ability to generate reactive oxygen species (ROS), such as hydroxyl radicals and superoxide anions, which can oxidize and break down polymer chains[27] (Figure 2). These nanoparticles can also act as electron donors or acceptors in redox reactions, further accelerating the degradation process[28]. The small size and high surface area of FeNPs make them highly reactive, enabling them to generate ROS under various environmental conditions[29].



**Figure 2. Properties of Iron nanoparticles**

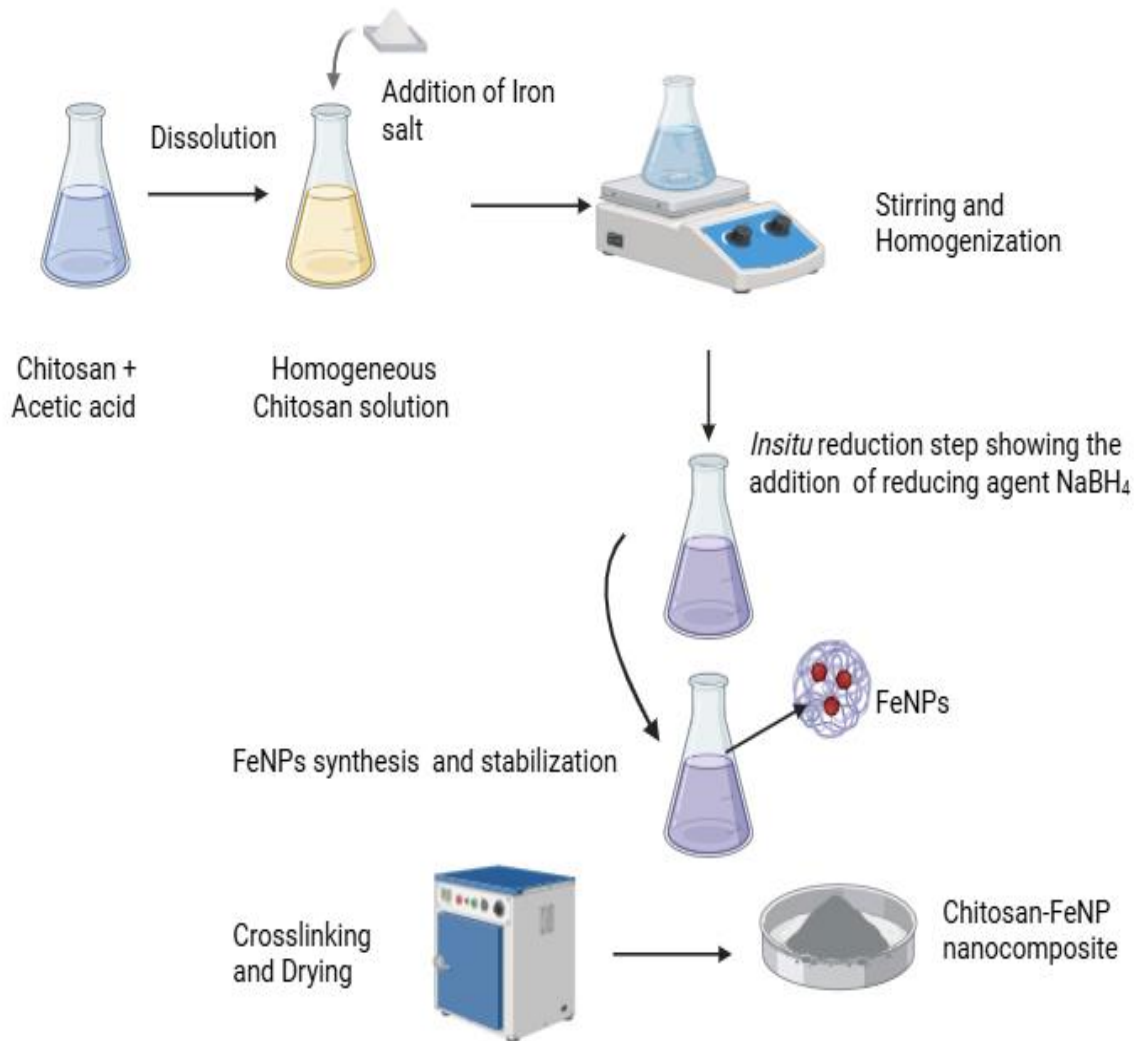
The mechanism of PE degradation action is defined with an oxidative cleavage of polymeric chains, where FeNPs catalyse the formation of hydroperoxides and carbonyl groups[29]. This transforms the inert plastic into smaller, oxygenated oligomers such as alcohols and carboxylic acids that microorganisms can finally digest[30]. FeNPs catalyse the Fenton and Fenton-like reactions that produce hydroxyl radicals, aiding oxidative degradation[30].



The  $OH^-$  radicals are highly reactive, which reacts with PE backbone to initiate the fragmentation

#### **Synthesis of Chitosan/ FeNP composites**

Chitosan/ FeNP composite is formed based on in-situ chemical reduction of iron salts within the polymer matrix[31]. In the synthesis, chitosan is dissolved in dilute acetic acid, the iron salts are added, further chemical reduction occurs in the presence of  $NaBH_4$ , the stability of the composite is based on the crosslinking structure in the composite, followed by washing and drying[19] ( Figure 3).



**Figure 3. Schematic representation for the synthesis of chitosan–FeNP nanocomposites via in situ reduction of iron salts in a chitosan matrix**

### **SYNERGISTIC MECHANISM OF CHITOSAN–FENP COMPOSITES IN POLYETHYLENE DEGRADATION**

Chitosan has a crucial role along with the stabilizing matrix in the degradation of polyethylene[20]. It prevents aggregation of iron nanoparticles, maintaining the catalytic efficiency, enhances the microbial adhesion and biofilm formation, improves the surface wettability of polyethylene through the dual action mechanism where, chemical degradation occurs in the presence of ROS and biological degradation by microbial colonization[32]. This synergy increases the degradation rates of polyethylene.

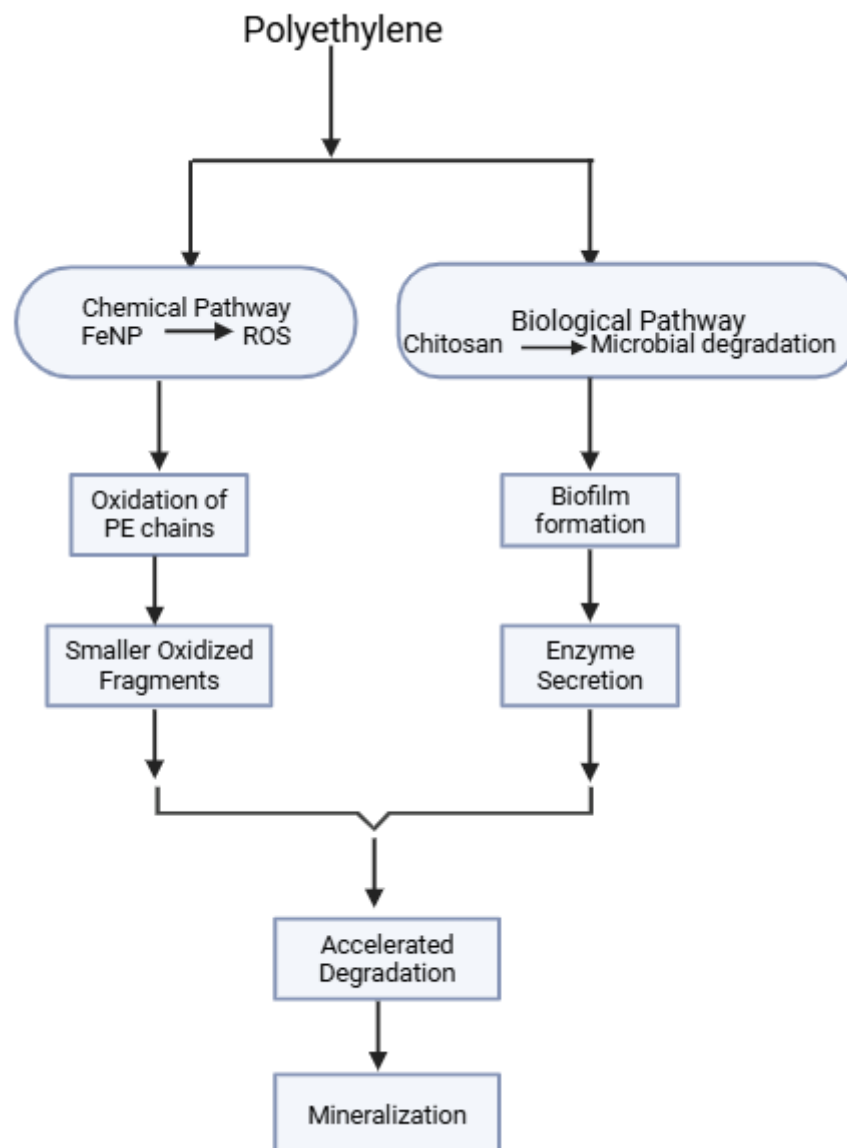
Chitosan and FeNPs when combined form the synergistic effect such as the composite enhances the hydrophilicity of PE, leading to surface modification[11]. Chitosan provides the controlled environment for sustained radical generation[33]. Exposure to UV light further accelerates the FeNP- mediated oxidation, leading to increased kinetics of breakdown of PE[33]. Thus, integration of chitosan and FeNPs results in a multifunctional degradation system with enhanced efficiency.

Key mechanism of the PE biodegradation includes the following steps: Catalytic oxidation where FeNPs generate hydroxyl radicals (-OH) that initiate the breaking of polymer chain[34]. Chitosan promotes the microbial attachment and biofilm formation on PE surfaces resulting in microbial enhancement[35]. It prevents the FeNP aggregation, maintaining the catalytic activity, resulting in controlled in the stability of nanoparticles[36]. The composite increases the surface hydrophilicity, improving the enzyme accessibility resulting in surface

modification[37]. Also, the photocatalytic enhancement results in increasing the ROS generation, which in turn improves the degradation kinetics[37].

FeNPs are particularly effective at breaking down PE through oxidative mechanisms through Fenton or Fenton-like reactions, which involve the breaking of polymer chains and the formation of smaller oligomers that are more easily biodegraded by microorganisms[38].

Recent work showed that FeNPs combined with chitosan enhanced the catalytic oxidation of PE, leading to the formation of short-chain hydrocarbons introducing oxygenated functional groups such as carbonyls, alcohols[39]. These smaller molecules are more susceptible to microbial degradation, thus accelerating the overall breakdown of PE[24]. Furthermore, FeNPs have been shown to aid in the depolymerization of PE by facilitating the formation of hydroperoxides, which act as intermediates in the oxidative degradation process[24] (Figure 4).



**Figure 4. Synergistic Degradation Pathway of Chitosan- FeNPs**

Studies have shown that FeNPs can effectively degrade various organic pollutants, including polyethylene. When FeNPs are combined with chitosan, they may form a composite material with enhanced catalytic activity. The chitosan matrix stabilizes the FeNPs, preventing their aggregation, and increases the overall efficiency of the polyethylene degradation process[40].

The combination of chitosan and FeNPs has been shown to provide a synergistic effect in the degradation of polyethylene. Chitosan not only stabilizes FeNPs but also enhances their catalytic activity by providing a supportive matrix[41]. Research has demonstrated that chitosan-FeNP composites could significantly improve the degradation of PE compared to either chitosan or FeNPs alone. The study showed that the FeNPs were well-dispersed within the chitosan matrix, which prevented their aggregation and allowed for more efficient interaction with the polyethylene surface[42].

It was found that the chitosan-FeNP composite led to increased formation of ROS, particularly hydroxyl radicals, which are highly effective in initiating the oxidative degradation of PE[43]. The study also reported a higher rate of microbial colonization on PE surfaces treated with chitosan-FeNP composites, further boosting the degradation process. Polyethylene degradation using chitosan combined with FeNPs typically involves both biological and chemical mechanisms:

**Microbial Degradation Enhancement:** Chitosan's biocompatibility allows it to interact with microbial communities, potentially enhancing their ability to degrade polyethylene. The FeNPs can facilitate the generation of ROS, which break down polyethylene's long hydrocarbon chains. The chitosan acts as a carrier for these microorganisms, stabilizing them and helping them attach more efficiently to the plastic surface[44].

**Catalytic Degradation by FeNPs :** Iron nanoparticles themselves play a crucial role in polyethylene degradation through their catalytic properties. FeNPs can induce the formation of hydroxyl radicals ( $\bullet\text{OH}$ ), which can attack the polyethylene polymer chains, breaking them down into smaller oligomers. This process accelerates the physical and chemical degradation of polyethylene, making it more susceptible to microbial attack[45].

**Enhancement in Degradation Efficiency:** The combination of chitosan and iron nanoparticles has shown significant improvements in the Polyethylene degradation compared to the conventional biological or chemical approaches[46]. Output from the use of chitosan – FeNP composites enhances the degradation efficiency by oxidative, catalytic, and microbial mechanisms[11].

Several studies have been made on the plastic degradation based on the application of chitosan – FeNP composites, which indicated that the efficiency of degradation rate depends on the nanoparticle size, oxidation state, chitosan concentration and environmental conditions[11].

Studies have demonstrated that the degradation of LDPE under aerobic conditions with a duration of 60 days indicated 32% of degradation[47]. Under UV- assisted conditions, HDPE has shown a considerable increase in carbonyl index for 30 days[48] [49]. Overall, research findings have shown that chitosan -FeNP composites have shown better performance than the individual components. This increase in the degradation rate can be related to increased surface area and reactivity of FeNPs, uniform dispersion of nanoparticles within the chitosan matrix, and improved interaction between the composite and polyethylene surface. The presence of chitosan confirms better contact between FeNPs and the polymer, thereby facilitating continuous catalytic activity.

**Role of Reactive Oxygen Species (ROS):** The degradation results in enhanced generation of reactive oxygen species (ROS) such as hydroxyl radicals ( $\bullet\text{OH}$ ). These radicals initiate the chain scission reactions, converting the long polyethylene chains into smaller, oxygenated intermediates.

The Fenton-like reactions catalyzed by FeNPs is as follows:  $\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \bullet\text{OH} + \text{OH}^-$

ROS generation is a primary driving force in the polyethylene degradation as it initiates the functional groups such as carbonyls and hydroxyls, increases polymer hydrophilicity, and also makes polyethylene more susceptible to microbial degradation

**Photocatalysis:** UV light accelerates FeNP-mediated ROS production enhancing degradation kinetics

## SYNTHESIS AND CHARACTERIZATION OF CHITOSAN -FENP COMPOSITES

### Synthesis of Chitosan–FeNP Composites

Chitosan–iron nanoparticle (Chitosan-FeNP) composites are synthesized using a variety of methods, typically involving **in-situ chemical reduction** of iron salts in the presence of chitosan. The general steps include:

Medium molecular weight Chitosan is dissolved in dilute acetic acid of 1 to 2% under constant stirring to obtain a homogeneous solution. The typical concentration is 1–2% (w/v).

$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  or  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  (for  $\text{Fe}^{3+}$  or  $\text{Fe}^{2+}$ ), sometimes in a 2:1 molar ratio to favor  $\text{Fe}_3\text{O}_4$  formation is used in the preparation. The iron salts are added dropwise into the chitosan solution under nitrogen or inert atmosphere to prevent premature oxidation.

Reducing agents such as  $\text{NaBH}_4$ , ascorbic acid, or hydrazine can be used. The reducing agent is added slowly, resulting in the formation of iron nanoparticles within the chitosan matrix. The mixture typically turns from yellow/brown to black, indicating FeNP formation.

Crosslinking Agents such as Glutaraldehyde or genipin may be added to improve the stability and mechanical strength of the composite. Crosslinking may also influence porosity and adsorption capacity.

The final composite is washed repeatedly with ethanol and distilled water to remove unreacted chemicals, followed by freeze-drying or oven-drying at low temperatures.

**Surface Modification and Structural Changes:** The combination of chitosan and FeNPs can also lead to surface modification of polyethylene, making it more hydrophilic and thus more accessible to microbial enzymes. This process increases the rate of polymer degradation by making the plastic surface more conducive to microbial colonization.

Characterization studies such as FTIR, SEM/TEM, XRD reveal substantial structural modifications in polyethylene after treatment like functional group interactions, morphology and dispersion and the crystalline phases during the degradation. EDX, TGA, VSM and BET studies have shown the elemental composition, thermal stability, magnetic properties and surface area and porosity in the degradation process.

The studies have shown the increased carbonyl index (C=O groups), formation of cracks, pits, and surface roughness also reduced molecular weight. These conditions promote progressive oxidation and fragmentation of the polymer. The formation of oxygenated groups is particularly important, as it transforms hydrophobic PE into a more biodegradable and hydrophilic material.

## CHARACTERIZATION OF CHITOSAN–FENP COMPOSITES

**Fourier Transform Infrared Spectroscopy (FTIR):** It identifies functional groups and interactions between chitosan and FeNPs. Shifts in –OH, –NH<sub>2</sub>, and C=O bands indicate bonding or coordination with iron ions.

**X-ray Diffraction (XRD):** The studies confirm the crystalline structure of FeNPs (e.g.,  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}^0$ , or  $\text{Fe}_2\text{O}_3$ ). The broad peaks from XRD may indicate nanoparticle size and phase purity.

**Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM):** The study reveals the surface morphology and dispersion of FeNPs in the chitosan matrix. TEM provides nanoparticle size distribution and core–shell structures.

**Energy-Dispersive X-ray Spectroscopy (EDX):** It confirms elemental composition and the presence of iron within the composite.

**Thermogravimetric Analysis (TGA):** It measures thermal stability and quantifies the inorganic content (FeNP loading). Chitosan degradation typically starts around 250°C, while FeNP residues remain stable.

**Vibrating Sample Magnetometry (VSM):** It evaluates magnetic properties if FeNPs are magnetite ( $\text{Fe}_3\text{O}_4$ ) or elemental Fe. It is useful for assessing reusability and magnetic separation capability.

**Brunauer–Emmett–Teller (BET) Surface Area Analysis:** It determines specific surface area, porosity, and adsorption potential. A high surface area enhances pollutant interaction and catalytic performance.

The synthesis of chitosan–FeNP composites is a straightforward and eco-friendly process that integrates the biocompatibility of chitosan with the high reactivity of iron nanoparticles. Comprehensive characterization is

essential to confirm successful synthesis, determine physicochemical properties, and optimize the composite for environmental applications such as pollutant degradation, adsorption, and catalysis.

**Influence of Environmental and Operational Parameters:** The degradation efficiency is strongly influenced by several factors, such as the size of nanoparticles, which provide higher surface area and reactivity, optimal levels of chitosan concentration are required for effective stabilization without diffusion limitations; pH and temperature affect Fenton reaction kinetics and microbial activity; presence of UV light enhances the ROS generation through photocatalysis also the type of polyethylene as LDPE is generally more susceptible than HDPE due to lower crystallinity. Hence, process optimization is very much essential for increasing the degradation rate.

Studies have indicated that the combined systems outperform individual treatments. UV and microbial co-treatment improve degradation kinetics. Also, efficiency depends on particle size, chitosan concentration, iron oxidation state, and polyethylene thickness

### ENVIRONMENTAL IMPLICATIONS AND CHALLENGES

The method is potential for green synthesis, ecofriendly and biodegradable, it is synergistic chemical – biological degradation, the biodegradation process is less toxic. Use of Chitosan matrix is environmentally friendly as it reduces the nanoparticle toxicity, enable controlled release and improve environmental compatibility. While the combination of chitosan and FeNPs shows promise for polyethylene degradation, several challenges remain.

One of the key concerns is the stability of FeNPs in environmental conditions[50]. Iron nanoparticles are prone to aggregation, which reduces their surface area and catalytic efficiency, during the degradation process, reducing the performance, the degradation efficiency is not consistent,

Recent studies have explored various methods to stabilize FeNPs, such as encapsulating them in polymers like chitosan or using surfactants to prevent agglomeration[51]. *Jin et al.* (2023) investigated the stabilization of FeNPs using chitosan and found that it significantly improved the longevity and effectiveness of the nanoparticles in polyethylene degradation.

However, ensuring long-term stability without compromising degradation efficiency is a significant challenge[52].

Another concern is the potential environmental impact of nanoparticles. While FeNPs are generally considered non-toxic, their long-term accumulation in the environment requires careful assessment, , hence monitoring of soil or water will be essential to check the concentration of nanoparticle. Some studies have suggested that the use of chitosan-FeNP composites could mitigate the potential release of toxic iron ions into the environment by providing a controlled release mechanism, reducing the risk of nanoparticle toxicity[53].

The efficiency of polyethylene degradation can vary depending on several factors, including the size and surface area of the FeNPs, the concentration of chitosan, and environmental conditions such as temperature and pH. Optimization of these parameters is necessary to achieve efficient degradation[52].

Also, the purification of high quality chitosan might be expensive compared to traditional methods. It also involves the scale up challenges. Also, some studies have indicated the partial degradation resulting in incomplete mineralization and many of these studies have limited to the laboratory conditions. Additionally, there is a lack of standardized methods for evaluating degradation, making cross-study comparisons difficult

### POTENTIAL APPLICATIONS

The combination of chitosan and FeNPs holds great potential for a wide range of applications. In waste management, this approach could provide a more sustainable solution for polyethylene degradation, reducing plastic waste in landfills and oceans[54]. Additionally, this method could be applied in bioremediation efforts, particularly in marine and freshwater ecosystems, where polyethylene waste is a significant issue.

Future research should focus on optimizing the properties of chitosan-FeNP composites to maximize the efficiency of polyethylene degradation. This includes exploring different chitosan formulations, varying FeNP sizes, and

adjusting environmental conditions such as pH and temperature to enhance the catalytic activity of FeNPs. Furthermore, large-scale applications and the potential integration of chitosan-FeNP composites in real-world waste management systems should be explored to evaluate their practical viability[55].

**Waste Management:** This approach can be utilized in waste management strategies to degrade polyethylene waste more effectively, reducing the burden of plastic pollution in landfills and oceans.

**Bioremediation:** The use of chitosan-FeNP composites could be integrated into bioremediation processes, where polyethylene waste is biodegraded in contaminated environments, such as marine ecosystems or urban settings.

**Development of Eco-Friendly Plastics:** In the long term, this technology may contribute to the development of biodegradable plastics that can be broken down in the environment more efficiently.

### ADVANTAGES AND LIMITATIONS

Advantages are the process is Eco-friendly and biodegradable; Low toxicity and safe for aquatic environments; can be produced using green synthesis routes. The method is potential for synergistic chemical and biological degradation

Limitations highlights Stability of FeNPs in the environment; high cost of chitosan purification; time-consuming degradation (weeks to months) Potential nanoparticle aggregation without surface modification

### FUTURE DIRECTIONS

The method is preferable for Bioaugmentation by combining microbial consortia with chitosan-FeNPs for enhanced bioremediation. The composite of Chitosan and Iron Nanoparticles offers a "green" pathway to tackle the plastic crisis, and future research should focus on Bioaugmentation by combining the composite with specific "plastic-eating" bacteria for plastic degradation. Studies are also aimed at the reusability and regeneration of the composite. Using the natural light / integrating the solar energy to increase the photocatalytic degradation. Research on emerging strategies such as magnetically recoverable nanocomposites and developing the pilot-scale reactors for treating municipal plastic waste and to make a thorough analysis Life cycle assessment (LCA) for the degradation of plastic is considered as a alternative approach for plastic waste management.

### CONCLUSION

Chitosan-incorporated iron nanoparticles represents a promising sustainable and effective approach to polyethylene degradation by combining nanocatalysis with biological enhancement.. The synergistic effects of these materials can enhance both the chemical and biological breakdown of polyethylene, offering a more sustainable and eco-friendly solution to plastic waste management.

The review also indicates that the polyethylene degradation is most effective as oxidative pretreatment and microbial degradation occur simultaneously. It addresses the major limitations of polyethylene degradation. The combination of catalytic oxidation, microbial enhancement, and material stabilization offers a promising pathway for sustainable plastic waste management.

While still in its developmental stages, this technique holds promise for large-scale application in mitigating plastic pollution. However, challenges related to the stability of nanoparticles, optimization of degradation conditions, and potential environmental impacts need to be addressed. Future research should focus on refining these techniques, developing scalable methods, and exploring the broader environmental implications of using nanoparticles in polymer degradation. This approach holds strong potential for advancing sustainable plastic waste management and contributing to a circular economy.

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