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Review: Utilization of Fe and Ni Green Nanoparticles in Waste Treatment to Enhance Pollutant Degradation Efficiency and Sustainability

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ABSTRAK

Meningkatnya kebutuhan akan teknologi degradasi polutan yang berkelanjutan dan efektif telah memicu minat pada nanoteknologi hijau sebagai solusi yang layak. Kajian ini menekankan penggunaan nanopartikel hijau logam non-mulia dalam aplikasi pengolahan limbah, yang menunjukkan kemampuannya untuk meningkatkan efisiensi degradasi polutan sekaligus memastikan keberlanjutan lingkungan. Topik utama yang dibahas meliputi metode sintesis yang menggunakan agen pereduksi alami dan ramah lingkungan, karakteristik fisikokimia nanopartikel logam non-mulia, Fe dan Ni dan mekanisme katalitiknya dalam berbagai proses pengolahan limbah. Studi perbandingan menyoroti manfaat logam Fe dan Ni, seperti efektivitas biaya, kelimpahan, dan dampak lingkungan yang lebih rendah. Paper ini juga mengkaji studi kasus yang menunjukkan penguraian polutan organik dan logam berat menunjukkan penggunaan praktis bahan-bahan ini. Tantangan seperti stabilitas, skalabilitas, dan potensi risiko lingkungan dianalisis secara menyeluruh, bersama dengan prospek masa depan untuk mengatasi hambatan ini. Tinjauan ini berupaya memberikan pemahaman terperinci tentang bagaimana nanopartikel hijau logam Fe dan Ni berkontribusi pada kemajuan teknologi pengolahan limbah berkelanjutan.

Kata Kunci: *nanoteknologi hijau, nanopartikel fe dan ni, pengolahan limbah, nanokatalis hijau, keberlanjutan lingkungan*

ABSTRACT

The growing need for sustainable and effective pollutant degradation technologies has sparked interest in green nanotechnology as a viable solution. This review emphasizes the use of non-noble metal green nanoparticles in waste treatment applications, showcasing their ability to improve pollutant degradation efficiency while ensuring environmental sustainability. Key topics covered include synthesis methods that employ natural and eco-friendly reducing agents, the physicochemical characteristics of non-noble metal nanoparticles, and their catalytic mechanisms in a variety of waste treatment processes. Comparative studies highlight the benefits of Fe and Ni, such as their cost-effectiveness, abundance, and lower environmental impact. This paper also presents case studies that demonstrate the breakdown of organic pollutants and heavy metals show the practical use of these materials. Challenges such as stability, scalability, and potential environmental risks are thoroughly analyzed, along with prospects to overcome these obstacles. This review seeks to provide a detailed understanding of how Fe and Ni green nanoparticles contribute to the advancement of sustainable waste treatment technologies.

Keywords*: green nanotechnology, fe and ni nanoparticles, waste treatment, green nanocatalyst, environmental sustainability.*

1. INTRODUCTION

The rapid expansion of industry and transportation has led to a significant increase in the production of lubricating oils, which in turn generates a substantial volume of waste oil [1]. As one of the world's most hazardous types of waste, it contains complex organic compounds, heavy metals, and toxic agents that are difficult to degrade naturally. If not managed properly, this waste can contaminate groundwater, soil, and ecosystems, leading to severe environmental and health issues. Therefore, an innovative approach is needed to effectively treat this waste. Nanotechnology, as a field focused on manipulating materials at the 1–100 nm scale, offers a promising solution [2]. At this nanoscale, materials exhibit unique properties such as an incredibly large surface area and heightened chemical reactivity, which are ideal for wastewater treatment applications, particularly for the effective breakdown of persistent hydrocarbons [3]. One of the most relevant applications of nanotechnology in waste treatment is the use of nanocatalysts (NCs).To ensure this process is environmentally friendly, green synthesis methods are the preferred choice [4]. Green synthesis is an approach that focuses on designing chemical products and processes that reduce or eliminate the use and generation of hazardous substances. This includes employing natural reducing agents like plant extracts, safe solvents such as water, and environmentally benign reaction conditions like low temperatures, as opposed to using toxic chemicals or high-energy processes. This study specifically focuses on developing nanocatalysts based on iron (Fe), nickel (Ni), and their alloy (FeNi). These elements were chosen for several reasons. Iron (Fe) is known for its catalytic properties, abundance, and relatively low toxicity [5]. Meanwhile, Nickel (Ni) demonstrates high catalytic activity, especially in hydrodeoxygenation and cracking reactions relevant to hydrocarbon degradation. The combination of both in an FeNi alloy can create a synergistic effect that enhances its stability and catalytic efficiency [6]. These unique properties make Fe, Ni, and FeNi nanocatalysts highly promising candidates for converting waste oil into more environmentally benign products, such as valuable fuels or chemicals. This research aims to explore the effectiveness of these green-synthesized Fe, Ni, and FeNi nanocatalysts in degrading waste oil, thereby highlighting their potential as an efficient and sustainable solution to this global environmental problem.

2. METODOLOGI

Synthesis method and application of Iron based, and Nickel based nanoparticles

A green NCs refers to a nanosized catalyst that is created and produced using eco-friendly methods, in line with the concepts of green chemistry. These concepts focus on reducing negative effects on the environment by substituting harmful chemicals with safer and more sustainable natural substances In the production of green NCs, natural extracts from plants are commonly utilized as reducing or stabilizing agents, such as extracts from *mangosteen peels* or grape seeds [7–9]. The use of these natural materials allows the synthesis to occur without relying on toxic organic solvents, which helps to minimize waste and lower the risk of harming the environment. These NCs have distinctive attributes due to their minuscule dimensions, which create a substantial surface area, thereby improving the effectiveness of chemical reactions [10]. The creation of environmentally friendly NCs is generally performed using energy-efficient techniques, such as microemulsion synthesis, which facilitates the generation of nanoparticles (NPs) at lower temperatures while minimizing energy use. This method is not only more sustainable and economical, as it makes use of commonly available and low-cost natural materials. The produced NCs show excellent catalytic performance, rendering them suitable for diverse applications in industries and WWT [11].

Various synthesis routes including physical, chemical, and biological methods have been employed to produce iron and nickel-based nanoparticles with desired properties tailored to their surface chemistry. Recent advancements in synthesis techniques, nanoparticle characterization, and applications have been comprehensively reported. These synthesis strategies are generally classified into top-down and bottom-up approaches. Physical methods fall under the top-down category, where bulk materials are broken down into nanoscale particles through a destructive process. In contrast, chemical and biological techniques are grouped under the bottom-up approach, in which nanoparticles are assembled from atomic or molecular precursors. Table 1 summarizes several commonly used synthesis methods for iron and nickel-based nanoparticles, outlining their main processes, advantages, and limitations to provide a clearer understanding of their applicability in various waste treatment and environmental remediation contexts.

Table 1. Preparation considerations of some preparation techniques of Iron based and Nickel based nanoparticle

Methods	Main activities occurred	Advantage	Disadvantage	References
Microemulsion	Water droplets dispersed in oil are stabilized by surface-active molecules, then subjected to surfactant removal and washing of the resulting colloidal material.	Variation in nanoparticles arises from the surfactant used, their intrinsic properties, and the surrounding physiological conditions.	Negative impacts of leftover surfactants on material properties and challenges in scaling up the process.	[12]
Hydrothermal	Hydrothermal reactions are performed in a reactor or autoclave in an aqueous media at higher temperatures and pressure above the solvent boiling point.	The dimensions and shapes can be readily adjusted.	High pressure and reaction temperature.	[13]
Sol-gel	It centers on the hydroxylation and condensation of molecular precursors in a solution, followed by “sol” drying or “gel” formation through either solvent evaporation or chemical reactions.	The aspect ratio, size, and internal structure are precisely regulated.	High permeability, weak bonding, low wear resistance.	[14]
Co-precipitation	The process involves reacting iron salts in an aqueous solution with a base in the presence of a gentle oxidizing agent, during which nucleation, particle growth, coarsening, and/or agglomeration occur simultaneously.	Simple and effective	Unsuitable for producing highly pure, accurately stoichiometric phases, as the pH must remain elevated throughout both the synthesis and purification stages.	[15]

2.1 Comparison with Previous Reviews and Novelty of the Study

Several previous studies have discussed green nanocatalysts based on Fe, Ni, and bimetallic FeNi; however, most have focused on single studies without comparing the performance among different types of catalysts. For instance, Sun et al**.** [16] reported the synthesis of Fe NPs using pomegranate leaf extract, which was capable of degrading indole pollutants with an efficiency of approximately 90% within 60 minutes at neutral pH. This study demonstrated the effectiveness of Fe NPs but did not present any comparison with Ni or FeNi. Another study by Balu et al. [17] used radish leaf extract to produce Fe NPs capable of degrading methylene blue and rhodamine B with an efficiency of 95–98% within 120 minutes under UV irradiation. Although the results were high, the scope of the study was limited to dye pollutants. For Ni NPs, Fardood et al. [18] synthesized NiO NPs using the natural reducing agent gum Arabic, which was applied to synthetic wastewater and achieved a degradation efficiency of approximately 85% within 90 minutes under acidic pH conditions. However, this study did not provide a performance comparison with Fe or FeNi.

Meanwhile, Parapat et al. [19] reported the synthesis of bimetallic FeNi/TiO_2 NPs using mangosteen peel extract for the pyrolysis of waste lubricating oil at 350 °C, achieving a conversion of over 90% into liquid fuel. Although promising, this study did not include a quantitative comparison with single-metal Fe or Ni. This study compiles and compares the performance data of Fe, Ni, and FeNi NPs synthesized through green methods from various literature sources. The comparison includes degradation efficiency against a wide range of pollutants (dyes, heavy metals, and waste oil), operating conditions, and synthesis methods (see table 2). The analysis results indicate that FeNi NPs generally exhibit higher efficiency than single metals, suggesting a synergistic effect in enhancing catalytic activity.

Table 2. Comparing the performance of Fe, Ni, and FeNi NPs in various studies

No	Reference	Type of Catalyst	Main Focus	Type of Pollutant	Synthesis Method	Notes on Limitations
1	Sun et al., [16]	Fe Nps	Degradation of organic pollutant (indole) using green-synthesized Fe	Indole (hazardous organic compound)	Pomegranate leaf extract as the reducing agent	No comparison with other metals; single focus on indole
2	Balu et al., [17]	Fe Nps	Photodegradation of textile dyes using green Fe NPs	Methylene Blue, Rhodamine B	Radish leaf extract as the reducing agent	Focused only on dye pollutants; did not test heavy metals or waste oil
3	Fardood et al., [18]	Ni Nps	Degradation of synthetic wastewater using green NiO NPs	Synthetic wastewater	Gum arabic as the reducing agent	No comparison with other metals
4	Parapat et al., [19]	FeNi/TiO2 NPs	Conversion of waste lubricating oil into liquid fuel through pyrolysis	Waste lubricating oil	Mangosteen peel extract as the reducing agent	Shows high conversion but without direct comparison to single-metal Fe/Ni
5	this review	Fe, Ni, FeNi Nps	Comparative analysis of the performance of green Fe, Ni, and FeNi on various pollutants	Dyes, heavy metals, waste oil	Natural reducing agents (mangosteen peel, grape seeds, etc.)	Combines data from various sources and demonstrates the synergistic effect of Fe–Ni

This review presents a quantitative comparative analysis of the performance of Fe NPs, Ni NPs, and bimetallic FeNi NPs synthesized through green methods, an approach that has not been directly reported in previous studies. The compiled data reveal a synergistic effect between Fe and Ni that enhances pollutant degradation efficiency compared to the use of single metals. Furthermore, this review provides catalyst performance data for a wide range of pollutants—organic, inorganic, and waste oil—thereby offering broader analytical coverage. The overall discussion reinforces the principle of sustainability by emphasizing the exclusive use of natural reducing agents in nanocatalyst synthesis, thus minimizing environmental impact and supporting the implementation of environmentally friendly technologies.

3. RESULT AND DISCUSSION

3.1 Green nanocatalyst and its applications in sustainability

Green metal NPs represent a category of environmentally friendly NCs that are extensively employed in waste management due to their capacity to purify water and air while minimizing the presence of harmful pollutants through different chemical reaction mechanisms. The primary benefit of green metal NPs is their capacity to improve the effectiveness of catalytic processes in decomposing or converting pollutants, whether they are organic or inorganic, into safer and less harmful environmental forms [20]. By facilitating oxidation, reduction, and photocatalysis reactions, green metal NPs can promote the breakdown of dangerous substances in waste. These NCs are particularly prominent in waste management due to their potential to cleanse water and air while diminishing toxic pollutants through various chemical reactions [21].

However, despite these significant advantages, green metal NPs also present critical challenges and risks that require careful evaluation. One of the foremost concerns is the potential toxicity and environmental impact of the nanoparticles themselves if not properly managed. Owing to their high reactivity and ability to penetrate biological tissues, these particles pose risks of bioaccumulation and long-term effects on ecosystems and human health [22,23]. Furthermore, large-scale production still faces technical and economic limitations, including maintaining particle size uniformity and achieving efficient scalability, which may hinder their practical applications [24,25]. Therefore, while NPs remain a promising innovation for sustainable waste treatment, a balanced approach that critically examines both the benefits and limitations is essential to ensure their safe and optimal deployment.

3.1.1 Iron NPs (Fe NPs)

Greenly synthesized iron NPs (Fe) refer to the creation of iron NPs utilizing natural resources, like plant extracts or microorganisms, to reduce iron ions (Fe^{2+} or Fe^{3+}) into Fe NPs. This method substitutes harmful chemicals typically employed in traditional synthesis, making it more eco-friendly and sustainable. Plant extracts rich in bioactive compounds such as flavonoids, polyphenols, or alkaloids function as reducing agents, converting iron ions into a more stable and efficient form of NPs [26]. Moreover, these compounds also act as stabilizers that inhibit the agglomeration or clustering of NPs, thereby preserving the size and catalytic characteristics of Fe NPs. However, despite offering a greener and more sustainable synthesis route, the production of Fe NPs through green methods is not without its challenges and risks. Variations in the chemical composition of plant extracts—arising from differences in plant species, cultivation conditions, or extraction techniques—can affect the consistency of nanoparticle size and morphology, ultimately influencing their quality and catalytic effectiveness [27].

Figure 1 illustrates the structure of Fe NPs produced using precursor/reducing agent concentration of 50%. At this concentration, the NPs are small and exhibit high homogeneity, yet they appear to cluster together, resulting in dense aggregates, likely due to enhanced interparticle interactions. Different NPs produced with natural reducers serve various roles in waste management and the enhancement of water quality. Fe NPs made from pomegranate leaf extract have been utilized to eliminate the pollutant indole [28]. NPs derived from *Calotropis gigantea* extract are effective in removing contaminants like heavy metals and organic substances to enhance water quality [29]. In addition, NPs created from radish leaf extract (*Raphanus* *sativus*) can effectively catalyze the degradation of challenging textile dyes, including methylene blue and rhodamine B [30].

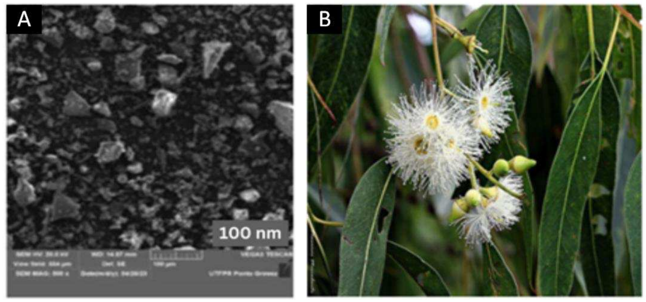

Figure 1. SEM image of Fe NPs (A) reduced by extract of *eucalyptus grandis* (B) [31]**.**

3.1.2 Nickel oxide NPs (NiO NPs)

Nickel oxide nanoparticles (NiO NPs) synthesized via green approaches harness the diverse phytochemical repertoire of plant extracts—including polysaccharides, polyphenols, flavonoids, and antioxidants—which function dually as reducing and capping agents. Through this biogenic route, nickel ions (Ni^{2+}) are transformed into uniformly distributed, catalytically potent NiO NPs in a process that is inherently eco-friendly and sustainable. The capping action of these biomolecules not only stabilizes the nascent nanoparticles and mitigates agglomeration but also obviates the reliance on toxic chemical reagents commonly employed in conventional synthesis protocols. However, the green synthesis of NiO NPs using plant extracts still faces several challenges and risks, as variations in the chemical composition of plant extracts driven by species differences, growth conditions, harvest season, and extraction methods can significantly influence nanoparticle size uniformity, morphology, and surface properties, potentially compromising their stability and catalytic performance [32].

The characterization of nickel oxide NPs (NiO NPs) reduced with *Arabic Gum* extract is illustrated in Figure 2 on the left side of the figure, the SEM photograph of NiO particles showcases their surface morphology, revealing nanometer-scale structures. This figure indicates that the NiO particles exhibit an irregular shape and small size that is uniformly distributed, a characteristic typical of NPs. On the right side of the figure, an Acacia tree is depicted, which yields *Arabic Gum*, a natural substance utilized as a reducing agent in the eco-friendly synthesis of NiO NPs. Employing *Arabic Gum* in this synthesis method highlights an environmentally sustainable strategy for creating nanomaterials, replacing harmful chemicals with natural alternatives. The integration of green synthesis techniques and the characterization of NPs morphology fosters the advancement of nanotechnology-based materials for various applications [33].

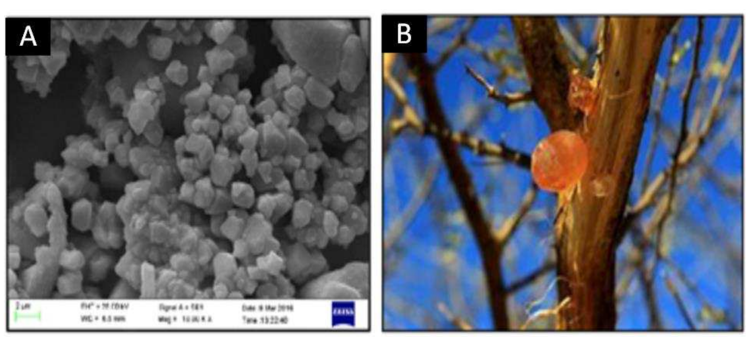

Figure 2. SEM image of NiO NPs (A) reduced by extract of *Arabic Gum* (B) [33]**.**

3.1.3 FeNi NPs

FeNi NPs created via the green synthesis approach utilize natural or eco-friendly substances as reducing and stabilizing agents for generating NPs of iron (Fe) and nickel (Ni). This method involves employing materials like plant extracts, bioactive compounds derived from plants, or microorganisms to convert Fe^{2+} and Ni^{2+} metal ions into stable FeNi NPs. Natural reducing agents, including flavonoids, tannins, or polyphenolic compounds found in plant extracts, facilitate the reduction of metal ions into NPs with small dimensions and large surface areas, thereby improving their catalytic activity. Moreover, these materials also function as stabilizing agents to ensure the stability of the NPs produced. The FeNi NPs generated through this green synthesis method hold significant potential for various applications, such as waste treatment, hazardous pollutant degradation, and water purification, owing to the synergistic catalytic effects of Fe and Ni that can expedite chemical reactions. Adopting the green synthesis methodology also minimizes the environmental impact typically associated with traditional synthesis methods, making it a more sustainable and eco-friendly option for manufacturing metal NPs.

Despite these advantages, the green synthesis of FeNi NPs faces several challenges and risks that warrant careful consideration. Variability in the chemical composition of natural reducing agents arising from differences in plant species, cultivation conditions, harvest season, and extraction processes can result in inconsistent particle size, morphology, and surface chemistry, thereby affecting catalytic efficiency and stability. Additionally, incomplete removal of residual biomolecules from the nanoparticle surface may alter their reactivity or introduce unintended toxicity, while large-scale production still encounters limitations in reproducibility, cost-effectiveness, and process control. Addressing these issues is essential to ensure the safe, reliable, and scalable application of FeNi NPs in environmental and industrial contexts [34].

Figure 3 presents the SEM characterization of FeNi/TiO_2 NCs prepared with *mangosteen peel* extract as the green reductant for pyrolysis of waste lubricating oil. The SEM characterization of the FeNi/TiO_2 material is depicted in Figure B, revealing particle agglomeration, where bright regions indicate a higher concentration of FeNi particles, while the darker regions correspond to TiO_2. Figure C presents the EDX spectrum, which verifies the presence of key elements including Fe, Ni, Ti, and O, highlighted by the distinct peaks for each element. The dominant high-intensity oxygen peak suggests a prevalence of oxides, further supporting the successful synthesis of FeNi/TiO_2 material as per the intended composition. The same results have also been reported by Parapat, et al. in previous studies [35].

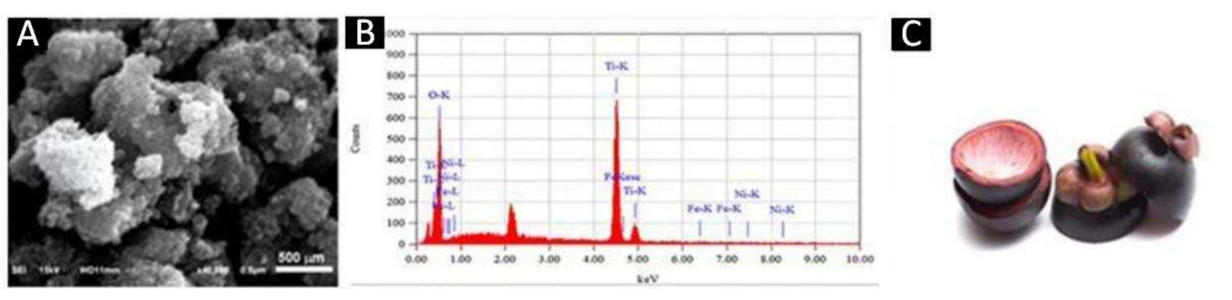

Figure 3. SEM images of the Fe–Ni/TiO_2 NCs at magnifications of 40000× (A). The corresponding EDS analysis (B) reduced by extract of Mangosteen Peel (A) [35].

3.2 The role of green nanocatalysts in waste treatment to enhance pollutant degradation, efficiency and sustainability

3.2.1 Technology for generating eco-friendly NCs

The technology designed for creating eco-friendly NCs focuses on producing environmentally safe NPs from natural resources such as plants and microorganisms, without the use of harmful chemicals. This approach is significant as it offers a safer and more sustainable method for treating pollutants, particularly in the context of WWT [36]. The biosynthesis of NPs involves the use of living organisms, including plants, bacteria, fungi, and algae. This process consists of the interaction between metal ions and biomolecules present in the organism, serving as reducing and stabilizing agents. Below are the primary mechanisms of biosynthesis: Plant extracts contain a variety of active compounds, including flavonoids, terpenoids, polyphenols, proteins, and antioxidants, which serve as reducing agents. Metal ions, like nickel ions (Ni^{+}) or iron ions (Fe^{2+}), are converted to their metallic state through a chemical process driven by these bioactive substances. Besides acting as a reducing agent, this compound also serves as a stabilizer for NPs, preventing them from clumping together and ensuring that the NPs remain evenly distributed and of consistent size [37]. For instance, extracts from the leaves of *Parthenocissus quinquefolia* have been utilized to synthesize iron and copper NPs. These NPs exhibit a significant ability to adsorb harmful dyes, such as malachite green, from water [38].

3.2.2 The role of green nanocatalysts in pollutant oxidation

Metals and their oxides are commonly utilized as catalysts. Recently, several types of modified metal oxides have been effectively tested as NCs for WWT. Metal oxide NPs such as ZnO, TiO_2, and CeO_2 have been thoroughly researched for their ability to degrade pollutants in water. The photocatalytic oxidation process is depicted in Figure 4. It demonstrates the photocatalytic mechanism of a heterostructure system featuring two primary materials, g-C_3N_4 (graphitic carbon nitride) and $BiVO_4$ (bismuth vanadate), with platinum (Pt) NPs acting as a co-catalyst. When these materials absorb light, electrons (e^-) in the valence band (VB) are excited to the conduction band (CB), creating holes (h^+) in the VB. In this heterostructure, electrons from the CB of $BiVO_4$ move to the CB of g-C_3N_4 due to the variation in their energy band positions, while the holes remain in their respective VB. This electron transfer decreases the recombination rate of electron-hole pairs, thereby improving the photocatalytic performance. The electrons that build up in the CB of g-C_3N_4 are subsequently transferred to the Pt NPs, where they interact with oxygen (O_2) to form superoxide radicals.

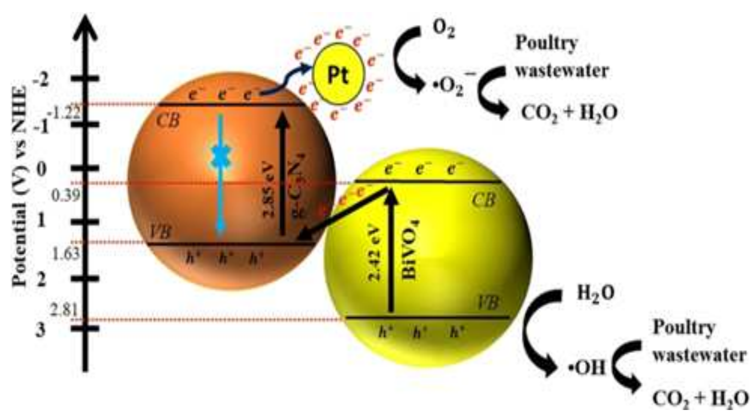

Figure 4. Illustration of the proposed photocatalytic mechanism of Pt/BiVO4/g–C3N4 [39].

Superoxide radicals and holes (h^+) are essential in the breakdown of poultry wastewater. The holes in the valence band of $BiVO_4$ and g-C_3N_4 interact with H_2O to generate hydroxyl radicals, which are highly effective in degrading organic compounds. In contrast, the superoxide radicals formed during the reduction of oxygen also aid in the oxidation of organic materials. This method efficiently transforms organic pollutants into carbon dioxide (CO_2) and water (H_2O), offering an eco-friendly approach to WWT. The integration of g-C_3N_4 and $BiVO_4$ in this heterostructure not only enhances the use of the light spectrum but also optimizes charge separation, thus improving degradation efficiency.

In waste management, nanomaterial catalysts can facilitate the chemical oxidation of organic pollutants. NPs composed of noble metals like Au, Pt, and Pd demonstrate strong catalytic capabilities for breaking down various organic substances and inorganic pollutants. When compared to traditional treatment methods, utilizing nano-catalysts for chemical oxidation presents numerous benefits, such as the ability to target resilient compounds, reducing processing duration, and converting waste into beneficial by-products. Palladium can effectively remove specific pollutants, including chlorinated hydrocarbons from wastewater, leading to potential commercial uses. NCs made from Pd/Fe_3O_4 exhibit excellent hydrodechlorination capabilities and can be easily retrieved using a magnetic field. Catalytic or photocatalytic oxidation represents an advanced technique for removing contaminants. This method can serve as a pre-treatment to boost biodegradability or act at the final stage to treat contaminants that are challenging to decompose. NCs that possess a high surface area-to-volume ratio exhibit superior oxidation performance. Variations in size lead to differences in band gap, crystal structure, redox potential, and charge distribution [21].

Green nanotechnology is being utilized across various sectors, including in the treatment of waste. NPs of metals and metal oxides generated through eco-friendly methods are commonly employed to eliminate contaminants from wastewater. An instance of this is the application of silver NPs synthesized using the extract from *P.thonningi* leaves, which have demonstrated efficacy in capturing heavy metals from synthetic wastewater. The wastewater that has been treated can subsequently be repurposed for either household or commercial use. Additional studies indicate that green iron oxide NPs synthesized from mandarin orange peel extract are effective in removing cadmium from waste, providing an economical and sustainable solution. Furthermore, TiO_2 NPs produced through eco-friendly methods have shown significant effectiveness in lowering chromium (Cr) levels and chemical oxygen demand (COD) in tannery wastewater, achieving a high success rate while utilizing a parabolic trough reactor. The use of natural and sustainable materials in the field of nanotechnology opens up opportunities for the development of non-toxic and biocompatible nanostructures [40].

3.2.3 Sustainability of environmental security

The application of green NCs in waste management presents considerable advantages regarding sustainability and environmental safety. NCs produced via green synthesis techniques not only minimize hazardous waste but also eliminate the need for toxic substances during the fabrication process. A primary concern is preventing NPs from escaping into the environment, as this could lead to long-term accumulation and potential ecotoxicity issues. Consequently, additional research is essential to develop green NCs that exhibit low toxicity and enhanced environmental safety. Assessing the ecotoxicity of new variations of NCs and conducting life cycle assessments of materials are vital to understanding their overall environmental impact. Green NCs derived from natural sources, such as plant extracts, have been shown to be safer in comparison to synthetic nanomaterials, and with more eco-friendly synthesis approaches, they can be scaled up at a reduced cost.

3.3 Challenges and Risks in the Development and Application of Fe, Ni, and FeNi-Based Green Nanocatalysts

Fe, Ni, and FeNi-based green nanocatalysts hold considerable promise for applications in waste remediation and sustainable fuel production. However, their safe and effective deployment requires overcoming several technical, environmental, and regulatory challenges. A primary technical limitation is the stability of these nanocatalysts. Fe, Ni, and FeNi nanoparticles are prone to agglomeration during storage or operation, leading to a reduction in active surface area and catalytic efficiency [16]. Achieving reproducible particle size and morphology via green synthesis is further complicated by variability in the phytochemical composition of plant extracts, which depends on seasonal, geographical, and extraction-method factors [41]. Such inconsistencies often result in performance variability between catalyst batches. Additionally, the catalytic activity of these materials can be restricted to narrow operational windows of pH and temperature [19].

From an environmental and toxicological perspective, even when synthesized via eco-friendly pathways, the uncontrolled release of Fe, Ni, or FeNi nanoparticles can present ecological hazards. Metallic nanoparticles have been shown to exert toxic effects on aquatic microorganisms, disrupt ecological balance, and induce oxidative stress in biota [42]. Ni is of particular concern due to its potential for bioaccumulation in the food web, while excess Fe in aquatic systems can promote eutrophication through excessive algal proliferation [43]. Furthermore, occupational or incidental human exposure—particularly via inhalation or dermal contact—may pose chronic health risks, with Ni recognized as a potential human carcinogen by the International Agency for Research on Cancer [44].

Scaling up green synthesis from laboratory to industrial production introduces further barriers. Although the use of natural reducing agents can lower chemical costs, industrial-scale processes require stringent parameter control, resulting in non-trivial operational expenses. The lack of internationally recognized quality standards for green nanocatalysts further exacerbates batch-to-batch performance discrepancies [17]. Addressing these limitations necessitates an integrated strategy. Optimizing green synthesis protocols to ensure consistent particle size and morphology, conducting comprehensive long-term ecotoxicological assessments on aquatic and terrestrial species, and developing closed-loop recovery systems are critical steps toward sustainable implementation. Equally important is cross-sector collaboration among academia, industry, and policymakers to establish global quality and safety standards. Such measures will be pivotal in advancing Fe-, Ni-, and FeNi-based green nanocatalysts from promising

4. CONCLUSION

The utilization of eco-friendly metal-free green NPs in waste management showcases remarkable potential in boosting pollutant breakdown effectiveness while fostering environmental stewardship. These NPs, produced through sustainable methods employing natural reducers like plant extracts, offer a green alternative to conventional chemical processes. Their distinctive physicochemical characteristics, including an extensive surface area and catalytic effectiveness, render them proficient in decomposing various organic and inorganic pollutants through mechanisms such as photocatalysis, fenton reactions, and adsorption. Nevertheless, obstacles persist in enhancing stability, scalability, and mitigating possible environmental hazards. Ongoing research concentrated on biosynthesis, material innovation, and lifecycle evaluation is crucial to surmounting these challenges and propelling green nanotechnology as a fundamental element for sustainable waste management strategies. This paradigm not only aids ecological preservation but also advances the wider objective of attaining sustainability in industrial and environmental practices.

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