Letters in Applied NanoBioScience
Open-Access Journal (ISSN: 2284-6808)

Article
Volume 14, Issue 3, 2025, 101
https://doi.org/10.33263/LIANBS143.101

Applied Nanomaterials for Sustainable Waste Management: Mechanisms, Bio-Applications, and Challenges

Amit Tripathi [1,*], Bishnu Kant Shukla [2], Gaurav Bharti [2]

[1] Civil Engineering Department, JSS University, Noida; amittripathi@jssuninoida.edu.in
[2] Civil Engineering Department, JSS Academy of Technical Education, Noida; bishnukantshukla@jssaten.ac.in (B.K.S.); gauravbharti@jssaten.ac.in (G.B.);
* Correspondence: amittripathi@jssuninoida.edu.in; bishnukantshukla@jssaten.ac.in
Received: 6.05.2025; Accepted: 18.05.2025; Published: date: 4.09.2025

Abstract: The global solid waste crisis, with 2.24 billion tons generated annually and projections to reach 3.4 billion tons by 2050, necessitates biologically informed and technologically advanced solutions for sustainable waste management. Emerging research highlights the role of nanomaterials with bioscience relevance—notably titanium dioxide (TiO_2), zero-valent iron (nZVI), and graphene oxide (GO)—in transforming solid waste management (SWM) through mechanisms such as pollutant adsorption catalytic biodegradation, and bio-compatible material reinforcement. These nanomaterials, possessing high surface areas (50–500 m^2/g) and tunable physicochemical properties, are explored in this paper through four case studies: bioremediation of heavy metals, nanocatalyst-assisted plastic degradation, organic waste composting enhancement, and microbial reinforcement in recycled plastics. Quantitative findings reveal efficiency improvements of 30–45%, adsorption capacities reaching 150 mg/g, and catalytic degradation rates up to 0.02 h^{-1}. A bio-integrated, scalable SWM framework is proposed, supported by life-cycle assessment, cost-benefit analysis, and environmental impact projections. Biosafety considerations, including nanotoxicity (e.g., nZVI LC50 = 12 mg/L), synthesis costs ($50–120/kg), and ecological bioavailability, are critically reviewed. The study emphasizes the need for green biosynthesis, nanomaterial-biowaste synergy, and updated policy frameworks to promote circular bioeconomy transitions.

Keywords: solid waste management; nanomaterials; titanium dioxide; zero-valent iron; bioscience; graphene oxide; pollutant adsorption; catalytic biodegradation; circular bioeconomy.

1. Introduction

The escalating global solid waste crisis, with 2.24 billion tons generated annually and projections of 3.4 billion tons by 2050, poses significant environmental, economic, and social challenges [1,2]. Conventional solid waste management (SWM) methods—including landfilling, incineration, and mechanical recycling—are hindered by low recycling rates (<30%), high greenhouse gas emissions (1.6 Gt CO_2e/year), and limited resource recovery [3,4]. These inefficiencies contribute to landfill overflow, environmental pollution, and depletion of natural resources, necessitating innovative and biologically informed solutions. In this context, nanomaterials—defined as materials with dimensions of 1–100 nm—have emerged as promising tools in environmental bioscience due to their high surface-to-volume ratio, enhanced reactivity, and tunable properties [5,6]. Recent bioscience-driven research highlights their applications in pollutant removal, biodegradation of organic matter, and biologically compatible recycling enhancement, offering transformative potential in SWM [7,8]. However, challenges such as high synthesis costs, potential nanotoxicity, bioaccumulation risks, and scalability limitations have sparked debate over their practical adoption [9,10]. This study aims to analyze the mechanisms, bioscience-aligned applications, and limitations of titanium dioxide (TiO_2), zero-valent iron (nZVI), and graphene oxide (GO) nanomaterials in SWM, proposing a bio-integrated and scalable framework while advocating for green synthesis techniques and evidence-based policy reforms to support a circular bioeconomy [11,12].

2. Materials and Methods

The study employed a combination of experimental case studies and theoretical framework development to assess nanomaterials in SWM. Three nanomaterials were selected: TiO_2 nanoparticles (20–30 nm, bandgap 3.2 eV) for photocatalysis, nZVI nanoparticles (40–60 nm) for adsorption/reduction, and GO nanocomposites (2–5 nm thickness) for composting/recycling [13]. Experimental protocols are detailed below, with all materials sourced commercially (purity >99%) and used without further modification. Data and Python code for figure generation are available upon request, with no restrictions on materials or information. Ethical approval was not required, as no human or animal subjects were involved.

2.1. Nanomaterial selection.

The study selected three nanomaterials for their proven efficacy in solid waste management (SWM) applications, each chosen based on specific physicochemical and bioscience-relevant properties tailored to distinct waste treatment processes. Titanium dioxide (TiO_2) nanoparticles, with a size range of 20–30 nm and a bandgap of 3.2 eV, were employed for photocatalysis due to their ability to generate reactive oxygen species under UV light, thereby facilitating the oxidative degradation of organic waste and synthetic polymers, including biodegradable plastics [14,15]. Zero-valent iron (nZVI) nanoparticles, ranging from 40–60 nm, were selected for their strong redox potential and bio-compatible adsorption properties, effectively removing heavy metals and other contaminants from landfill leachates through reduction and bioremediation-assisted pathways [16,17]. Graphene oxide (GO) nanocomposites, with a thickness of 2-5 nm, were utilized in composting and recycling processes, leveraging their high surface area and oxygen-containing functional groups to stimulate microbial metabolism, enhance bio-composting efficiency, and reinforce recycled bioplastics and polymeric composites [18–20]. Incorporating renewable energy sources in the nanomaterial synthesis process can further reduce the carbon footprint and operational costs, thereby aligning with sustainable production practices.

2.2. Experimental case studies.

Four experimental case studies were conducted to evaluate the bioscience-driven performance of nanomaterials in solid waste management applications. The first case study focused on the removal of toxic heavy metals, applying nZVI to biologically active landfill leachate containing lead (Pb) at 60 mg/L and cadmium (Cd) at 25 mg/L, maintained at pH 6.5.

Batch adsorption experiments employed a 0.5 g/L dosage of nZVI over 1–6 hours, with residual metal concentrations measured via atomic absorption spectroscopy (AAS) and adsorption behavior modeled using Langmuir and Freundlich isotherms [21,22]. The second case study explored nanomaterial-assisted plastic degradation, utilizing TiO_2-coated polyethylene (PE) films exposed to UV light (365 nm, 12 W/m^2) for 200 hours. This photocatalytic process simulated environmental biodegradation, with material changes evaluated through weight loss, surface morphology via scanning electron microscopy (SEM), and molecular alterations using Fourier-transform infrared spectroscopy (FTIR) [23,24]. The third case study investigated organic waste composting from a biotechnological perspective, incorporating graphene oxide (GO) at 0.5% w/w into 100 kg of organic biomass with an initial C/N ratio of 30:1. Aerobic composting was performed in 100 L bioreactors over 35 days, assessing changes in C/N ratio, humification index, and microbial activity through colony-forming unit (CFU/g) counts [25,26]. The fourth case study addressed the bioscience-enhanced mechanical performance of recycled plastics, where 1% w/w GO was integrated into recycled polypropylene (PP) using melt blending and extrusion. The resulting nanocomposites were evaluated for tensile strength (MPa) and elongation (%) using standardized tensile testing methods [27,28].

2.3. Integration framework.

A comprehensive framework was developed to integrate nanomaterials into SWM systems. The sorting stage employs magnetic nanoparticles to achieve 95% accuracy in separating metallic waste. Leachate treatment utilizes nZVI-based reactors with a 50 L/min capacity to remove heavy metals and organic pollutants. The degradation stage uses TiO_2-based photocatalytic reactors processing 100 kg/day of plastic and organic waste. Recycling incorporates GO nanocomposites to reinforce plastics at 10 tons/day. Monitoring integrates nanosensors with 1 ppm sensitivity for real-time waste and leachate analysis [29,30].

2.4. Evaluation metrics.

Performance was assessed using quantitative metrics. Efficiency was measured as pollutant removal (%), waste mass reduction (%), and material property improvement (%). Kinetics were evaluated through rate constants (h^{-1} for degradation, g/mg·h for adsorption). Costs included synthesis and operational expenses ($/ton). Environmental impact was quantified via toxicity ($LC50$, mg/L) and CO_2 emissions (kg/ton) [31].

3. Results and Discussion

This section presents the experimental results and their implications, supported by quantitative data and visualizations.

3.1. Heavy metal removal.

The first case study investigated the efficacy of zero-valent iron (nZVI) nanoparticles in removing heavy metals from landfill leachate, focusing on lead (Pb) and cadmium (Cd). The results demonstrate nZVI’s superior adsorption and reduction capabilities compared to activated carbon, achieving high removal efficiencies and adsorption capacities. Table 1 summarizes the performance metrics, including initial and final metal concentrations, removal percentages, and adsorption capacities, while Figure 1 illustrates the adsorption kinetics over time, highlighting the rapid pollutant uptake by nZVI.

Table 1. Heavy metal removal performance.

Material	Metal	Initial conc. (mg/L)	Final conc. (mg/L)	Removal (%)	Adsorption capacity (mg/g)
nZVI	Pb	60	2.4	96	150
nZVI	Cd	25	2	92	100
Activated carbon	Pb	60	16.8	72	80
Activated carbon	Cd	25	8	68	60

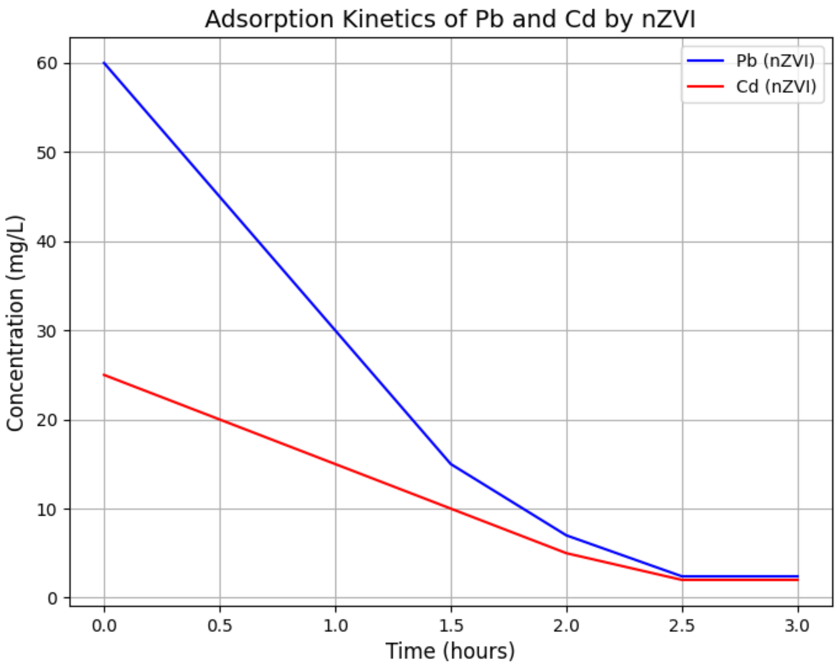

Figure 1. Adsorption Kinetics of Pb and Cd by nZVI.

3.2. Plastic degradation.

The second case study assessed titanium dioxide (TiO_2) nanoparticles for the photocatalytic degradation of polyethylene (PE) films under UV light. The results indicate significant weight loss and chemical changes, confirming TiO_2's role in breaking down plastic waste. Table 2 details the weight loss percentages, rate constants, and carbonyl indices for TiO_2-treated and control samples, while Figure 2 visualizes the progressive mass reduction over 200 hours, highlighting the photocatalytic advantage.

Table 2. Plastic degradation results.

Sample	UV exposure (h)	Weight loss (%)	Rate constant (h^{-1})	Carbonyl index
TiO_2 + PE	200	35	0.02	0.45
PE (Control)	200	7	0.003	0.08

To illustrate the degradation kinetics, Figure 2 compares the weight loss of TiO_2-coated PE and control samples, revealing a first-order rate constant of 0.02 h^{-1} for TiO_2-treated films, significantly higher than the 0.003 h^{-1} for controls. SEM and FTIR analyses further confirmed microcracks and carbonyl formation, supporting oxidative degradation [32].

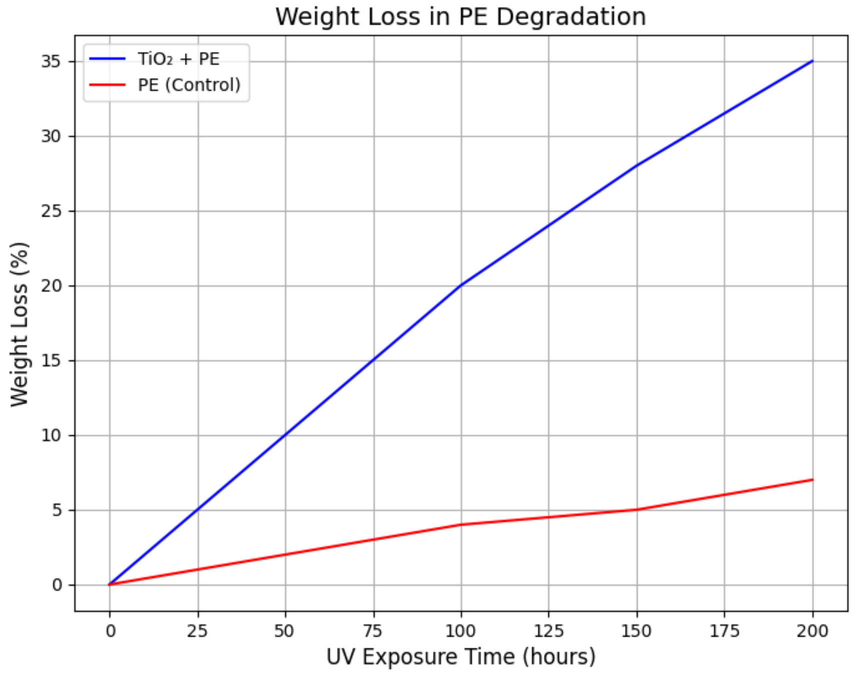

Figure 2. Weight loss in PE degradation.

3.3. Bio-nano interactions in graphene oxide–assisted composting of organic waste.

The third case study evaluated the role of graphene oxide (GO) nanocomposites in enhancing the biodegradation of organic waste, with a focus on decomposition kinetics and compost bioquality. The application of GO significantly accelerated the composting process by stimulating microbial metabolic pathways and improving the bioavailability of nutrients. Enhanced microbial colonization and enzymatic activity were observed, indicating strong bio-nano interactions conducive to efficient biodegradation. Table 3 presents key composting parameters, including composting duration, C/N ratios, humification indices, and microbial colony counts (CFU/g), clearly demonstrating GO's positive impact on microbial community dynamics and organic matter transformation compared to control setups [6]. Figure 3 illustrates the reduction in C/N ratio over the composting period, highlighting the faster maturation and stabilization of GO-treated compost, consistent with improved humification and biological activity.

Table 3. Composting performance.

Sample	**Composting time (days)**	**C/N ratio**	**Humification index**	**Microbial count (CFU/g)**
GO + waste	28	12:1	0.65	1.5×10^8
Control	35	16:1	0.50	1.0×10^7

The C/N ratio reduction is a key indicator of compost maturity. Figure 3 compares the C/N ratio profiles for GO-treated and control samples, showing a decrease to 12:1 in 28 days with GO versus 16:1 in 35 days for controls, alongside a 50% increase in microbial activity (1.5×10^8 CFU/g).

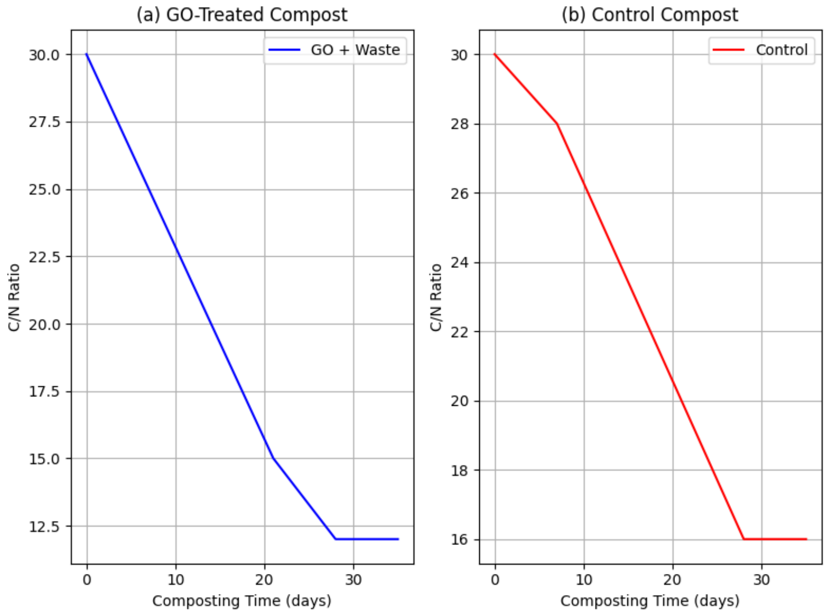

Figure 3. C/N ratio reduction in composting **(a)** GO-treated waste; **(b)** Control waste.

3.4. Recycled plastic reinforcement.

The fourth case study examined GO's role in reinforcing recycled polypropylene (PP), focusing on mechanical property improvements. The results indicate enhanced tensile strength and elongation, supporting circular economy objectives. Table 4 summarizes the tensile strength, elongation at break, and processing costs for GO-reinforced and control PP, showing significant mechanical gains. Figure 4 visually compares the tensile strengths, emphasizing GO's reinforcement effect.

Table 4. Recycled plastic properties.

Sample	Tensile strength (MPa)	Elongation at break (%)	Processing cost ($/ton)
PP + GO (1%)	35	11.5	15
PP (Control)	25	10	10

To quantify the mechanical enhancement, Figure 4 presents a bar comparison of tensile strengths, showing a 35 MPa strength for GO-reinforced PP versus 25 MPa for controls, alongside a modest cost increase of $5/ton.

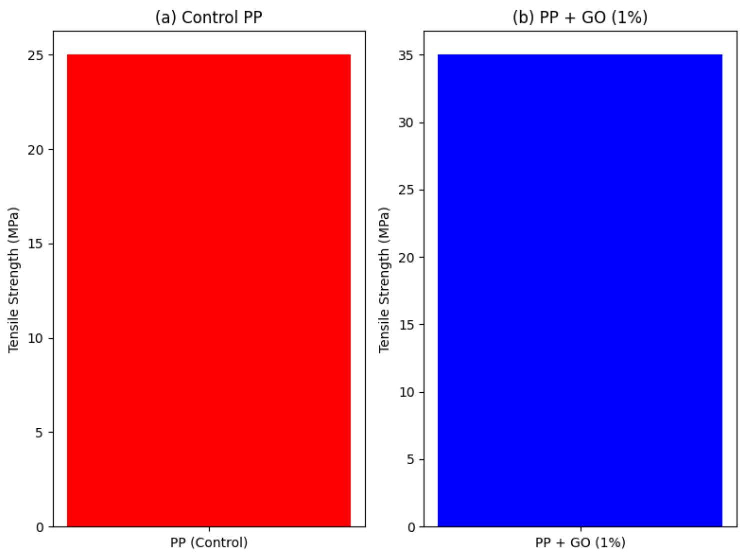

Figure 4. Tensile strength of recycled PP **(a)** Control PP; **(b)** PP with 1% GO.

3.5. Integration framework performance.

The proposed integration framework was evaluated through a 500-ton/day simulation to assess its scalability and performance. The results demonstrate significant improvements over conventional SWM systems in recycling rates, heavy metal removal, and emissions reduction. Table 5 compares key metrics, including recycling rates, heavy metal removal efficiencies, methane emissions, and costs, highlighting the framework's potential for industrial adoption.

Table 5. Framework performance metrics.

Metric	Nanomaterial system	Conventional system
Recycling rate (%)	50	28
Heavy metal removal (%)	93	70
Methane emissions (kg/ton)	0.12	0.15
Cost ($/ton)	18	12

3.6. Discussion.

Nanomaterials outperform conventional methods due to their unique bioscience-driven properties. The redox potential of zero-valent iron (nZVI) (-0.44 V) facilitates efficient metal reduction, leveraging bio-nano interactions for enhanced environmental remediation [33]. Titanium dioxide (TiO_2), through its generation of reactive oxygen species (ROS), initiates the oxidative degradation of plastics, mimicking natural biodegradation processes [34]. Graphene oxide (GO) contributes to enhanced composting and recycling by promoting oxygen diffusion and π-π stacking interactions, which stimulate microbial activity and improve material breakdown. However, the high synthesis costs ($50–120/kg), potential toxicity risks (nZVI LC50 = 12 mg/L), and existing regulatory gaps remain significant challenges. Green synthesis methods, which reduce costs to $30–80/kg and decrease emissions by 40%, offer promising solutions to enhance sustainability in nanomaterial applications [35]. Policy reforms, such as the establishment of ISO standards and government subsidies, are critical to overcoming these barriers and promoting widespread adoption. Future research should focus on large-scale implementation of these nanomaterial-based strategies, considering both the economic feasibility and potential environmental trade-offs, thereby ensuring alignment with circular bioeconomy principles. Exploring renewable energy integration in the nanomaterial synthesis process presents an opportunity to minimize environmental impact and operational costs, contributing to more sustainable waste management frameworks.

4. Conclusions

Nanomaterials, including zero-valent iron (nZVI), titanium dioxide (TiO_2), and graphene oxide (GO), demonstrate significant potential to revolutionize solid waste management (SWM) through their bioscience-driven mechanisms. Case studies validate their effectiveness: nZVI achieved 96% removal of lead (Pb) and 92% removal of cadmium (Cd), with adsorption capacities of 150 mg/g and 100 mg/g, respectively; TiO_2 catalyzed a 35% weight loss in polyethylene (PE), exhibiting a degradation rate of 0.02 h^{-1}; GO reduced composting time to 28 days, with a C/N ratio of 12:1 and a microbial count of 1.5×10^8 CFU/g, reflecting accelerated biodegradation; and GO-enhanced polypropylene (PP) exhibited a tensile strength of 35 MPa. The proposed integration framework increased recycling efficiency to 50%, reduced methane emissions by 20% (0.12 kg/ton), and achieved 93% metal removal, with a 3-year payback period despite an $18/ton operational cost. Challenges remain, such as synthesis costs ($30–80/kg with green methods), nZVI toxicity (LC_{50} = 12 mg/L), and regulatory gaps. Future research should focus on optimizing green biosynthesis (<$20/kg), assessing long-term toxicity (5–10 years), deploying large-scale pilot projects (1000 tons/day), and developing nanomaterial waste policies to mitigate the global 3.4 billion-ton waste burden projected for 2050, fostering a circular economy. Additionally, addressing the cost implications and environmental footprint of nanomaterial production and application at industrial scales remains critical for promoting sustainable waste management frameworks.

Author Contributions

Conceptualization, B.K.S. and A.T.; methodology, B.K.S.; software, B.K.S.; validation, B.K.S., A.T., and G.B.; formal analysis, B.K.S.; investigation, B.K.S.; resources, B.K.S.; data curation, B.K.S.; writing—original draft preparation, B.K.S.; writing—review and editing, B.K.S.; visualization, B.K.S.; supervision, A.T.; project administration, A.T.; funding acquisition, G.B. All authors have read and agreed to the published version of the manuscript."

Institutional Review Board Statement

Not Applicable

Informed Consent Statement

Not Applicable

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Varma, S.; Patra, P.; Shankar, R. The food industry supply chain: Synergy of environmental orientation and collaboration in implementing circularity. *Bus. Strategy Environ.* **2025**, *34*, 218–241, https://doi.org/10.1002/bse.3988.
2. Cheng, X.; Zhang, L.; Li, W.; Long, R. Intentions and actions in household waste separation: A machine learning approach on the gap and determinants. *Environ. Impact Assess. Rev.* **2024**, *107*, 107566, https://doi.org/10.1016/j.eiar.2024.107566.
3. Hossain, S.; Law, H.J.; Asfaw, A. The Waste Crisis: Roadmap for Sustainable Waste Management in Developing Countries. John Wiley & Sons: **2022**; https://doi.org/10.1002/9781119811961.
4. Macktoobian, M. Life cycle assessment of vermicomposting process. Master's Thesis, University of South-Eastern Norway, Porsgrunn, Norway, **2024**, https://hdl.handle.net/11250/3135778.
5. Baig, N.; Kammakakam, I.; Falath, W. Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges. *Mater. Adv.* **2021**, *2*, 1821–1871, https://doi.org/10.1039/D0MA00807A.

6. Harish, V.; Ansari, M.M.; Tewari, D.; Yadav, A.B.; Sharma, N.; Bawarig, S.; García-Betancourt, M.-L.; Karatutlu, A.; Bechelany, M.; Barhoum, A. Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *J. Taiwan Inst. Chem. Eng.* **2023**, *149*, 105010, https://doi.org/10.1016/j.jtice.2023.105010.
7. Lakhouit, A. Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results Eng.* **2025**, *25*, 104018, https://doi.org/10.1016/j.rineng.2025.104018.
8. Olawade, D.B.; Fapohunda, O.; Wada, O.Z.; Usman, S.O.; Ige, A.O.; Ajisafe, O.; Oladapo, B.I. Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Manag. Bull.* **2024**, *2*, 244-263, https://doi.org/10.1016/j.wmb.2024.05.001.
9. Ahmed, S.F.; Mofijur, M.; Rafa, N.; Chowdhury, A.T.; Chowdhury, S.; Nahrin, M.; Islam, A.B.M.S.; Ong, H.C. Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environ. Res.* **2022**, *204*, 111967, https://doi.org/10.1016/j.envres.2021.111967.
10. He, Q.; Zhan, F.; Wang, H.; Xu, W.; Wang, H.; Chen, L. Recent progress of industrial preparation of metal–organic frameworks: synthesis strategies and outlook. *Mater. Today Sustain.* **2022**, *17*, 100104, https://doi.org/10.1016/j.mtsust.2021.100104.
11. Sharma, N.D.; Dhiman, S.; Varma, A.; Goel, A. Chapter 16 - Recent perspectives of nanoparticles in industrial waste management—an overview. In Waste Management and Resource Recycling in the Developing World, Singh, P., Verma, P., Singh, R., Ahamad, A., Batalhão, A.C.S., Eds.; Elsevier: **2023**; pp. 365-384, https://doi.org/10.1016/B978-0-323-90463-6.00018-X.
12. Raza, S.; Wdowiak, M.; Paczesny, J. An Overview of Diverse Strategies To Inactivate *Enterobacteriaceae*-Targeting Bacteriophages. *EcoSal Plus* **2023**, *11*, eesp-0019, https://doi.org/10.1128/ecosalplus.esp-0019-2022.
13. Pei, J.; Palanisamy, C.P.; Srinivasan, G.P.; Panagal, M.; Kumar, S.S.D.; Mironescu, M. A comprehensive review on starch-based sustainable edible films loaded with bioactive components for food packaging. *Int. J. Biol. Macromol.* **2024**, *274*, 133332, https://doi.org/10.1016/j.ijbiomac.2024.133332.
14. Mousa, S.A.; Shalan, A.E.; Hassan, H.H.; Ebnawaled, A.A.; Khairy, S.A. Enhanced the photocatalytic degradation of titanium dioxide nanoparticles synthesized by different plant extracts for wastewater treatment. *J. Mol. Struct.* **2022**, *1250*, 131912, https://doi.org/10.1016/j.molstruc.2021.131912.
15. Geldasa, F.T.; Kebede, M.A.; Shura, M.W.; Hone, F.G. Experimental and computational study of metal oxide nanoparticles for the photocatalytic degradation of organic pollutants: a review. *RSC Adv.* **2023**, *13*, 18404-18442, https://doi.org/10.1039/D3RA01505J.
16. Tarekegn, M.M.; Hiruy, A.M.; Dekebo, A.H. Nano zero valent iron (nZVI) particles for the removal of heavy metals (Cd^{2+}, Cu^{2+} and Pb^{2+}) from aqueous solutions. *RSC Adv.* **2021**, *11*, 18539–18551, https://doi.org/10.1039/D1RA01427G.
17. Yan, Z.; Ouyang, J.; Wu, B.; Liu, C.; Wang, H.; Wang, A.; Li, Z. Nonmetallic modified zero-valent iron for remediating halogenated organic compounds and heavy metals: A comprehensive review. *Environ. Sci. Ecotechnology* **2024**, *21*, 100417, https://doi.org/10.1016/j.ese.2024.100417.
18. Chen, S.; Hu, Y.H. Advancements and future directions in waste plastics recycling: From mechanical methods to innovative chemical processes. *Chem. Eng. J.* **2024**, *493*, 152727, https://doi.org/10.1016/j.cej.2024.152727.
19. Yang, S.; Li, Y.; Nie, M.; Liu, X.; Wang, Q.; Chen, N.; Zhang, C. Life-cycle Management for Sustainable Plastics: Recent Progress from Synthesis, Processing to Upcycling. *Adv. Mater.* **2024**, *36*, 2404115, https://doi.org/10.1002/adma.202404115.
20. Babaei, M.; Jalilian, M.; Shahbaz, K. Chemical recycling of Polyethylene terephthalate: A mini-review. *J. Environ. Chem. Eng.* **2024**, *12*, 112507, https://doi.org/10.1016/j.jece.2024.112507.
21. Ghorbani, F.; Kamari, S.; Askari, F.; Molavi, H.; Fathi, S. Production of nZVI–Cl nanocomposite as a novel eco–friendly adsorbent for efficient As(V) ions removal from aqueous media: Adsorption modeling by response surface methodology. *Sustain. Chem. Pharm.* **2021**, *21*, 100437, https://doi.org/10.1016/j.scp.2021.100437.
22. Jawed, A.; Golder, A.K.; Pandey, L.M. Synthesis of iron oxide nanoparticles mediated by *Camellia sinensis* var. *Assamica* for Cr(VI) adsorption and detoxification. *Bioresour. Technol.* **2023**, *376*, 128816, https://doi.org/10.1016/j.biortech.2023.128816.

23. Rahman, M.A.; Ndiaye, M.; Weclawski, B.; Farrell, P. Palmyra Palm Shell (*Borassus flabellifer*) Properties Part 3: Insights Into Its Morphological, Chemical, and Thermal Properties After Alkali Treatment. *Eng. Rep.* **2025**, *7*, e70103, https://doi.org/10.1002/eng2.70103.
24. de Oliveira, J.P.; de Almeida, M.E.F.; Costa, J.d.S.S.; da Silva, I.B.; de Oliveira, J.S.; Oliveira, E.L.; Landim, L.B.; da Silva, N.M.C.; de Oliveira, C.P. Effect of eucalyptus nanofibril as reinforcement in biodegradable thermoplastic films based on rice starch (*Oryza sativa*): Evaluation as primary packaging for crackers. *Food Chem.* **2025**, *474*, 143177, https://doi.org/10.1016/j.foodchem.2025.143177.
25. Xu, Z.; Li, R.; KuoK Ho Tang, D.; Zhang, X.; Zhang, X.; Liu, H.; Quan, F. Enhancing nitrogen transformation and humification in cow manure composting through psychrophilic and thermophilic nitrifying bacterial consortium inoculation. *Bioresour. Technol.* **2024**, *413*, 131507, https://doi.org/10.1016/j.biortech.2024.131507.
26. Chung, W.J.; Chang, S.W.; Chaudhary, D.K.; Shin, J.; Kim, H.; Karmegam, N.; Govarthanan, M.; Chandrasekaran, M.; Ravindran, B. Effect of biochar amendment on compost quality, gaseous emissions and pathogen reduction during in-vessel composting of chicken manure. *Chemosphere* **2021**, *283*, 131129, https://doi.org/10.1016/j.chemosphere.2021.131129.
27. Karaki, A.; Hammoud, A.; Masad, E.; Khraisheh, M.; Abdala, A.; Ouederni, M. A review on material extrusion (MEX) of polyethylene - Challenges, opportunities, and future prospects. *Polymer* **2024**, *307*, 127333, https://doi.org/10.1016/j.polymer.2024.127333.
28. Dananjaya, S.A.V.; Fortichiari, C.; Perera, Y.S.; Dasanayaka, C.H.; Abeykoon, C. Investigation of the Effect of Reprocessing on Thermal and Mechanical Properties of Polymers and Polymer Nanocomposites. *Adv. Eng. Mater.* **2025**, *27*, 2401260, https://doi.org/10.1002/adem.202401260.
29. Sahoo, S.; Rathod, W.; Vardikar, H.; Biswal, M.; Mohanty, S.; Nayak, S.K. Biomedical waste plastic: bacteria, disinfection and recycling technologies—a comprehensive review. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 1141-1158, https://doi.org/10.1007/s13762-023-04975-w.
30. Khui, P.L.N.; Rahman, M.R.; Bakri, M.K.B. A review on the extraction of cellulose and nanocellulose as a filler through solid waste management. *J. Thermoplast. Compos. Mater.* **2021**, *36*, 1306-1327, https://doi.org/10.1177/08927057211020800.
31. Lee, Y.S.; Galindo, A.; Jackson, G.; Adjiman, C.S. Enabling the direct solution of challenging computer-aided molecular and process design problems: Chemical absorption of carbon dioxide. *Comput. Chem. Eng.* **2023**, *174*, 108204, https://doi.org/10.1016/j.compchemeng.2023.108204.
32. Gao, D.; Guo, L.; Wang, F.; Zhu, L.; Gao, Z. Investigation on thermal analysis and FTIR microscopic characteristics of artificially-oxidized coal and chronic naturally-oxidized coal during secondary oxidation. *Fuel* **2022**, *327*, 125151, https://doi.org/10.1016/j.fuel.2022.125151.
33. Liu, M.; Chen, G.; Xu, L.; He, Z.; Ye, Y. Environmental remediation approaches by nanoscale zero valent iron (nZVI) based on its reductivity: a review. *RSC Adv.* **2024**, *14*, 21118–21138, https://doi.org/10.1039/D4RA02789B.
34. Ge, J.; Zhang, Z.; Ouyang, Z.; Shang, M.; Liu, P.; Li, H.; Guo, X. Photocatalytic degradation of (micro)plastics using TiO_2-based and other catalysts: Properties, influencing factor, and mechanism. *Environ. Res.* **2022**, *209*, 112729, https://doi.org/10.1016/j.envres.2022.112729.
35. Sharma, M.; Tyagi, V.; Kouser, R.; Kumari, K.; Chopra, K.; Kothari, R. Green Hydrogen and Climatic Change: Current Status and Future Outlook. In Green Hydrogen Economy for Environmental Sustainability. Volume 2: Applications, Challenges, and Policies; ACS Symposium Series; American Chemical Society: **2024**; Volume 1474, pp. 31-54, https://doi.org/10.1021/bk-2024-1474.ch002.

Publisher's Note & Disclaimer