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Green Chemistry Strategies for Mitigating Microplastic Pollution in Aquatic Environments

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Abstract
Microplastic pollution poses a growing threat to aquatic ecosystems. This review explores green chemistry strategies for mitigating this issue. The focus is on preventing microplastic generation at the source. Strategies include designing plastic products for reusability and recyclability, developing biodegradable plastics, and utilizing alternative materials. Improved wastewater treatment processes to capture microplastics before they enter aquatic environments are addressed. Biodegradable plastics and microplastic capture methods in wastewater treatment facilities are highlighted as promising green solutions. Green chemistry principles are emphasized throughout, highlighting the importance of environmentally friendly solutions. By implementing these strategies, we can significantly reduce microplastic pollution and protect our precious water resources.

Keywords: *Sustainability, green chemistry, aquatic, microplastics, pollution.*

1. Introduction

Microplastic pollution has emerged as a major environmental issue, posing significant threats to aquatic ecosystems worldwide. These tiny plastic particles, which are typically invisible to the naked eye, are caused by the breakdown of larger plastic waste or are deliberately produced for various applications. Their widespread prevalence in marine and freshwater ecosystems has caused concerns about their impact on aquatic life, human health, and ecosystem integrity (1). Microplastics are microscopic plastic particles with a diameter of less than five millimeters that are produced as a result of both commercial product development and breakdown of bigger plastics. They are divided into two types: primary microplastics, such as microfibers from textiles and microbeads in cosmetics, and secondary microplastics, which are created by the degradation of bigger plastic products like water bottles owing to causes such as sunshine and waves (2). These tiny plastic particles pose significant environmental and health dangers. Microplastics in aquatic environments can be consumed by aquatic organisms, potentially causing harm to marine life and ecosystems. They have been found in marine organisms, commercial seafood, and even drinking water, raising concerns about the potential impact on human health as seen in fig 1. Microplastics can also build in soil, influencing soil characteristics, microbes, and animals, with possible implications for human health and the environment (3).

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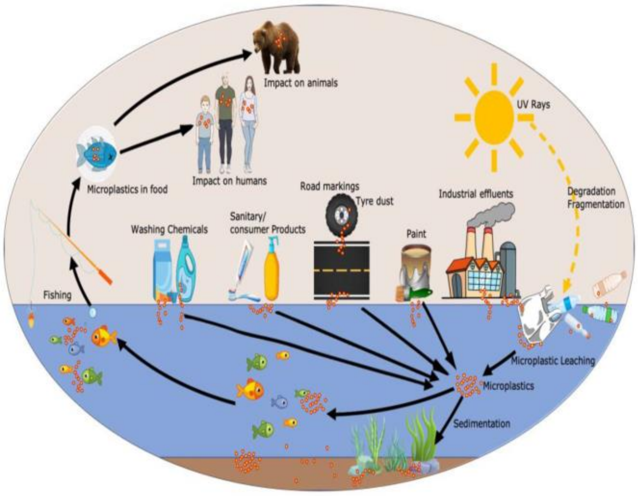

Figure 1. Microplastics generation, transportation and ingestion in the environment affecting the whole ecosystem (4).

Green chemistry offers promising strategies to mitigate plastic pollution in aquatic ecosystems. The principles of green chemistry as shown in fig 2 centres on the design, synthesis, and disposal of chemicals and materials with the goal of reducing or eliminating hazardous substances (5).

One important component of green chemistry is the development of analytical methods that minimize the usage of harmful solvents and reagents. This is particularly significant in the detection of microplastics, because standard procedures may unintentionally produce environmentally harmful compounds. Green analytical chemistry techniques seek to minimize waste, energy consumption, and the usage of hazardous compounds throughout the analytical process (6). Another green chemistry technique involves using coagulants and flocculants to improve microplastic removal from wastewater. Previous studies have shown that using the right chemicals can effectively remove even tiny microplastics from wastewater, preventing their release into aquatic habitats. Green chemistry, by enhancing coagulation and flocculation processes, can help to remove microplastics more effectively from wastewater.

Green chemistry principles can help guide the design of alternative materials that are inherently less damaging to the environment. This includes creating biodegradable or recyclable polymers that do not remain in the environment as microplastics. Green chemistry can contribute to the development of more sustainable alternatives to conventional plastics by focusing on the complete material life cycle, from synthesis to disposal (7-8).

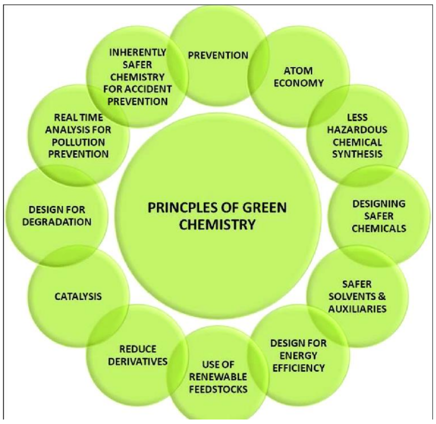

Figure 2. Principles of green chemistry (5)

2. Pathways of Microplastic Entry into Aquatic Environments

Microplastics, which are plastic particles smaller than five millimetres, can pose serious biological and environmental problems when they infiltrate aquatic habitats through a variety of channels (9). The following are the primary entrance points for microplastics into aquatic environments:

1) Primary Microplastics: These are the microplastics that are purposefully made for a particular function, including the synthetic fibres found in textiles, the microbeads in personal care products, and the pellets used to make plastic (10). Primary microplastics enter aquatic habitats directly through industrial effluents, runoff from production sites, wastewater discharges, and transportation-related plastic pellet spills.
2) Secondary Microplastics:Plastic items like bottles, bags, and fishing gear degrade over time due to physical, chemical, and biological processes. UV radiation, mechanical abrasion, wave action, and microbial activity break down these items into smaller fragments, generating secondary microplastics (11). Plastics used in construction, transportation, and marine activities can also undergo abrasion, releasing microplastic particles into the environment, such as tires and boat hulls.
3) Atmospheric Deposition: Through precipitation, atmospheric fallout, and dry deposition, microplastics can travel great distances through the atmosphere and end up in aquatic habitats. Airborne microplastics are emitted into the atmosphere as airborne particles or fibres from sources including metropolitan areas, industrial sites, agricultural fields, and marine ecosystems (12). Airborne microplastics can reach aquatic bodies by direct deposition or surface runoff after they are deposited.
4) Sewage and Wastewater Effluents: Domestic, industrial, and agricultural wastewater and sewage effluents release microplastics into aquatic habitats. Microplastic pollution in wastewater is caused by plastic trash flushed down toilets, microbeads from personal care items, and synthetic fibres lost from clothing during laundry (13). While some microplastics may be eliminated by treatment facilities, a sizable amount can still enter rivers, lakes, and the ocean through effluent discharges.
5) Surface Runoff: Microplastics are carried into aquatic habitats from land-based sources by urban and agricultural runoff. Litter, plastic trash, and microplastics from streets, sidewalks, and storm drains are carried into rivers, streams, and coastal waters by urban runoff from rainwater (14). In a similar vein, runoff from agriculture pollutes water bodies with soil particles, fertilisers, pesticides, and plastic waste from fields.
6) Natural Sources: Although natural sources sometimes contribute to the existence of microplastics in aquatic habitats, human activities are the main cause of microplastic contamination (15). These include the disintegration of biodegradable polymers and fibres formed from plants, as well as the weathering and erosion of naturally occurring objects that contain microplastics, such as volcanic rocks, sand grains, and organic matter.

3. Green Chemistry Approaches for Microplastic Mitigation

3.1 Biodegradable Polymers

Biodegradable polymers are a promising alternative to conventional plastics due to their environmentally friendly properties. These materials can be broken down into simpler, non-toxic compounds by microorganisms, reducing pollution and environmental impact. They offer a sustainable solution to plastic waste accumulation and are versatile for various industries. Biodegradable polymers are environmentally friendly, reducing pollution and harm to ecosystems (16). They are sourced from renewable resources, reducing reliance on finite fossil fuel reserves. They can be engineered to possess specific properties, such as flexibility, strength, and biocompatibility, making them suitable for various applications. Some biodegradable polymers are compatible with living tissues, allowing their use in biomedical applications without adverse effects (17). Additionally, biodegradable polymers offer comparable mechanical properties to conventional plastics.

Biodegradable polymers are used in various applications as sustainable alternatives to traditional plastics. They are used in food packaging, agriculture, medical and healthcare, consumer goods, and textiles (18). Biodegradable mulch films, plant pots, and agricultural nets reduce plastic waste and environmental contamination. They are also used in surgical sutures, drug delivery systems, tissue engineering scaffolds, and biodegradable implants. They are also used in disposable cutlery, cups, straws, and hygiene products, providing eco-friendly alternatives to single-use plastics. They are also used in clothing, footwear, and textile fibers (19).

Biodegradable microbeads are replacing microbeads in personal care products, reducing microplastic pollution in water bodies (20). Fishing gear made from biodegradable polymers break down in marine environments, reducing the risk of entanglement and ingestion by marine animals. Biodegradable packaging materials degrade into harmless compounds in composting facilities, preventing microplastic accumulation in soil and water. Biodegradable mulch films made from polymers like PLA or PBS degrade after use in agriculture, reducing soil contamination and microplastic release into the environment (21).

3.2 Eco-Friendly Additives and Coatings

As the negative effects of traditional plastics on ecosystems and human health become more apparent, there is an urgent need for sustainable alternatives that reduce environmental damage while keeping plastics' functionality and versatility. Eco-friendly additives and coatings play an important role in this paradigm change by increasing the biodegradability, recyclability, and environmental compatibility of plastics (22). These additives and coatings are intended to improve the inherent qualities of plastics, making them more suitable for eco-friendly disposal and lowering their environmental footprint throughout their existence. Eco-friendly additives and coatings, which use renewable resources, creative formulations, and green chemistry principles, pave the way for a more sustainable future in plastic manufacture, consumption, and waste management (23)

3.2.1 Role of Additives and Coatings in Enhancing Biodegradability and Reducing Microplastic Fragmentation

Some additives and coatings enhance biodegradability by stimulating microbial activity, promoting the breakdown of plastics by microorganisms in various environments like soil, water, and composting facilities. These additives provide nutrients or substrates that promote microbial colonization and enzymatic degradation, leading to the formation of harmless compounds like water, carbon dioxide, and biomass. They also facilitate hydrolytic degradation, breaking down polymer chains into smaller fragments through hydrolyzable bonds or chemical groups. This process enables microbial assimilation and mineralization of plastic waste. Additionally, some additives and coatings catalyze oxidative degradation processes, such as oxidation or photodegradation, which break down plastic polymers into smaller, more biodegradable fragments (24). This process generates reactive oxygen species (ROS), making plastics more susceptible to microbial attack and enzymatic degradation.

Additives and coatings can enhance the durability and mechanical integrity of plastics, reducing their susceptibility to fragmentation and abrasion. These additives enhance tensile strength, flexibility, and impact resistance, mitigating physical stressors that lead to microplastic generation. Surface modification can reduce friction, adhesion, and wear on plastic surfaces, minimizing abrasion and fragmentation. Surface-modifying coatings provide a protective barrier against environmental factors like UV radiation, moisture, and chemical exposure. Anti-fouling properties, such as biocides or surface-active compounds, inhibit the attachment and growth of organisms on plastic surfaces, reducing the accumulation of organic matter and debris that can exacerbate microplastic fragmentation and degradation in aquatic environments (25).

Several examples of sustainable additives and coatings have shown promise in mitigating microplastic pollution by enhancing the biodegradability of plastics and reducing fragmentation. Enzymes like lipases, esterases, and proteases can be added to plastics to facilitate enzymatic degradation. These additives accelerate the breakdown of polymer chains into smaller fragments, making plastics more accessible for microbial assimilation and biodegradation in natural environments. Studies show these additives enhance plastic biodegradability and reduce microplastic persistence in soil, water, and composting facilities. Also, oxo-biodegradable additives, which contain transition metal salts and pro-degradant catalysts, accelerate the oxidative degradation of plastics. These additives reduce the persistence of plastics as macroplastics by fragmenting them into smaller fragments under exposure to oxygen and UV radiation, promoting microbial degradation (26). However, concerns about microplastic pollution arise from incomplete degradation and fragmentation processes. Natural compounds like chitosan, lignin, and cellulose can be used as additives or coatings to improve the biodegradability and environmental compatibility of plastics. These natural alternatives offer renewable, biocompatible alternatives to petroleum-based additives, reducing the environmental impact of plastics. Chitosan, derived from crustacean shells, improves plastics' biodegradability in marine environments, while lignin and cellulose-based coatings enhance water resistance and mechanical properties (27). Bio-based polymers like PLA, PHA, and PBS are sustainable alternatives to traditional petroleum-based plastics. These renewable materials are biodegradable, compostable, and recyclable. PLA undergoes enzymatic hydrolysis, transforming into lactic acid, which can be metabolized by microorganisms. PHA and PBS offer similar benefits, reducing microplastic pollution and promoting circularity in plastic production and waste management.

3.3 Advanced Filtration and Remediation Technologies

Green filtration technologies utilize sustainable and environmentally friendly methods to remove contaminants from water, air, or other fluids. Biofiltration involves the use of living organisms like bacteria, fungi, and plants to degrade or remove contaminants from air or water. In water biofiltration, microorganisms break down organic pollutants, nutrients, and pathogens through biological processes like biodegradation and adsorption. In air biofiltration, microorganisms convert gaseous pollutants into harmless by-products like water and carbon dioxide. Adsorption filtration involves binding contaminants onto a solid surface, such as activated carbon, zeolites, or biochar, through physical or chemical interactions. This method effectively removes a wide range of pollutants, including organic compounds, heavy metals, and micropollutants, from water and air streams (28). Membrane filtration uses semi-permeable membranes to separate contaminants from water or air based on size, charge, or solubility. Different processes include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, each with varying pore sizes and filtration capabilities. Membrane filtration is effective in removing suspended solids, bacteria, viruses, salts, and dissolved contaminants from water, producing clean and potable water for drinking, industrial processes, and wastewater treatment.

Green filtration technologies have various efficiency and cost-effectiveness factors that influence their effectiveness. Biofiltration systems can remove organic pollutants and pathogens with high removal efficiencies, but their performance may vary based on factors like temperature, pH, and nutrient availability. Adsorption filtration is effective but may require frequent regeneration or replacement of adsorbent materials. Membrane filtration processes offer high removal efficiencies for a wide range of contaminants but may be influenced by fouling, scaling, and membrane integrity issues. The cost-effectiveness of green filtration technologies depends on capital investment, operational expenses, maintenance requirements, and the lifespan of filtration systems. Biofiltration systems may have lower capital costs but higher operating and maintenance costs due to regular monitoring, nutrient supplementation, and system optimization. Adsorption filtration systems may incur expenses related to procurement and regeneration of adsorbent materials and energy consumption for system operation (29). Membrane filtration systems typically have higher capital costs but lower operating costs, offering long-term cost savings through reduced chemical usage, energy consumption, and waste disposal.

Green filtration technologies contribute to sustainable water and air management practices, promoting resource conservation, pollution prevention, and ecosystem protection. However, membrane filtration processes may generate concentrate streams or membrane waste, posing environmental challenges related to energy consumption and waste management (30).

4. Emerging Trends and Innovations in Green Chemistry for Microplastic Mitigation

Green chemistry principles are increasingly being used to develop long-term solutions to prevent the spread of microplastics in aquatic environments. Researchers are working to create less hazardous synthesis processes for chemicals and solvents used in a variety of industries, including organic synthesis and pollutant extraction (31). Green chemistry is helping to create a more sustainable industrial landscape by reducing the negative environmental effects of chemical production processes. In today's waste recycling scenario, value-added fractions, such as monomers and functional components, are recovered from complex waste items such as composite and unsorted plastics (32). Green chemistry seeks to lessen the environmental impact of plastic waste by improving waste recycling procedures. Studies such as the techno-economic assessment of co-generation of food packaging bioplastic and food supplements from edible microalgae show that sustainable bioplastic manufacturing processes are economically viable. Such assessments shed light on the profitability and feasibility of green chemistry approaches to microplastic reduction (33-35).

Conclusion

The Increasing threat of microplastic pollution in aquatic environments demands innovative solutions. This article explored green chemistry strategies that tackle the problem at its source, emphasizing prevention over remediation. These strategies focus on designing plastic products for reusability and recyclability, developing biodegradable polymers, and exploring alternative materials altogether. Green chemistry principles were underscored throughout, promoting environmentally friendly solutions across the plastic lifecycle. Microplastic pollution is a significant environmental threat to aquatic ecosystems worldwide. Green chemistry offers a promising approach to mitigating this issue by focusing on preventing plastic pollution at its source. Biodegradable polymers can be broken down by microorganisms, reducing plastic accumulation in the environment. They are derived from renewable resources and can be used in various applications, including packaging, agriculture, and textiles. Eco-friendly additives and coatings can enhance the biodegradability and recyclability of existing plastics. This reduces their environmental impact throughout their lifecycle. By implementing green chemistry strategies like these, we can significantly reduce microplastic pollution in aquatic environments. However, continued research and development are necessary to improve the performance, scalability, and cost-effectiveness of these solutions.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Li, Z., Yang, Y., Chen, X., He, Y., Bolan, N., Rinklebe, J., Lam, S. S., Peng, W., & Sonne, C. (2024). Occurrence, transport, and toxicity of microplastics in tropical food chains. *Environmental Science and Pollution Research International*, *1-5*. doi: 10.1016/j.chemosphere.2022.137637
2. Koelmans, B., Pahl, S., Backhaus, T., Bessa, F., van Calster, G., Contzen, N., Cronin, R., Galloway, T., Hart, A., Henderson, L., & Wyles, K. (2019). A scientific perspective on microplastics in nature and society. *SAPEA*. doi: 10.26356/microplastics
3. Woychik, R. (2024, May). Microplastics' knowns, unknowns discussed by a physician-scientist. *Environmental Factor*. Retrieved from https://factor.niehs.nih.gov/2024/5/feature/4-feature-microplastics-and-nanoplastics

4. Angnunavuri, S. R., & Smith, M. (2020). Microplastics: A review of sources, effects, and management strategies. *Environmental Science and Pollution Research*, *27*(10), *1-12*. doi: 10.1007/s11356-020-10251-4
5. Ghosh, S., Sinha, J. K., Ghosh, S., Vashisth, K., Han, S., & Bhaskar, R. (2023). Microplastics as an emerging threat to the global environment and human health. *Sustainability*, *15*(14), *10821*. doi: 10.3390/su151410821
6. Barrick, A., Champeau, O., Chatel, A., Manier, N., Northcott, G., & Tremblay, L. A. (2021). Plastic additives: Challenges in ecotox hazard assessment. *PeerJ*, *9*, *e11300*. doi: 10.7717/peerj.11300
7. Alero, M., Godoy, V., Quesada, L., & Martín-Lara, M. Á. (2021). Green strategies for microplastics reduction. *Current Opinion in Green and Sustainable Chemistry*, *28*, *100442*. doi: 10.1016/j.cogsc.2020.100442
8. Picó, Y., & Barceló, D. (2021). Analysis of microplastics and nanoplastics: How green are the methodologies used? *Current Opinion in Green and Sustainable Chemistry*, *31*, *100503*. doi: 10.1016/j.cogsc.2021.100503
9. Du, S., Zhu, R., Cai, Y., Xu, N., Yap, P. S., Zhang, Y., He, Y., & Zhang, Y. (2021). Environmental fate and impacts of microplastics in aquatic ecosystems: A review. *RSC Advances*, *11*(26), *15762-15784*. doi: 10.1039/d1ra00880c
10. Corinaldesi, C., Canensi, S., Dell'Anno, A., et al. (2021). Multiple impacts of microplastics can threaten marine habitat-forming species. *Communications Biology*, *4*, *431*. doi: 10.1038/s42003-021-01961-1
11. Moore, C. (2024, April 19). Plastic pollution. *Encyclopedia Britannica*. Retrieved from https://www.britannica.com/science/plastic-pollution
12. Torres-Agullo, A., Karanasiou, A., Moreno, T., & Lacorte, S. (2021). Overview on the occurrence of microplastics in air and implications from the use of face masks during the COVID-19 pandemic. *Science of The Total Environment*, *800*, *149555*. doi: 10.1016/j.scitotenv.2021.149555
13. Sun, J., Dai, X., Wang, Q., van Loosdrecht, M. C. M., & Ni, B. J. (2019). Microplastics in wastewater treatment plants: Detection, occurrence and removal. *Water Research*, *152*, *21-37*. doi: 10.1016/j.watres.2018.12.050
14. Ragoobur, D., Huerta-Lwanga, E., & Somaroo, G. D. (2021). Microplastics in agricultural soils, wastewater effluents and sewage sludge in Mauritius. *Science of The Total Environment*, *798*, *149326*. doi: 10.1016/j.scitotenv.2021.149326
15. Kumar, A., & Krishan, G. (2024). Microplastic pollutants in aquatic ecosystems: Present and future challenges. *Water*, *16*, *102*. doi: 10.3390/w16010102
16. Gross, R. A., & Kalra, B. (2002). Biodegradable polymers for the environment. *Science*, *297*(5582), *803-807*. doi: 10.1126/science.297.5582.803
17. Kurowiak, J., Klekiel, T., & Będziński, R. (2023). Biodegradable polymers in biomedical applications: A review—developments, perspectives and future challenges. *International Journal of Molecular Sciences*, *24*(23), *16952*. doi: 10.3390/ijms242316952
18. Baranwal, J., Barse, B., Fais, A., Delogu, G. L., & Kumar, A. (2022). Biopolymer: A sustainable material for food and medical applications. *Polymers*, *14*, *983*. doi: 10.3390/polym14050983
19. Vroman, I., & Tighzert, L. (2009). Biodegradable polymers. *Materials (Basel)*, *2*(2), *307-344*. doi: 10.3390/ma2020307

20. Gamage, S., & Mahagamage, Y. (2024). Microplastics in personal care products and cosmetics in Sri Lanka. *Heliyon*, *10*(8), *e29393*. doi: 10.1016/j.heliyon.2024.e29393
21. Merino, D., Zych, A., & Athanassiou, A. (2022). Plasticizers and the effects of migration into food. *ACS Applied Materials & Interfaces*, *14*(41), *46920-46931*. doi: 10.1021/acsami.2c10965
22. Maddela, N. R., Kakarla, D., Venkateswarlu, K., & Megharaj, M. (2023). Additives of plastics: Entry into the environment and potential risks to human and ecological health. *Journal of Environmental Management*, *348*, *119364*. doi: 10.1016/j.jenvman.2023.119364
23. Landrigan, P. J., et al. (2023). The Minderoo-Monaco Commission on Plastics and Human Health. *Annals of Global Health*, *89*(1), *23*. doi: 10.5334/aogh.4056
24. Kola, V., & Carvalho, I. S. (2023). Plant extracts as additives in biodegradable films and coatings in active food packaging. *Food Bioscience*, *54*, *102860*. doi: 10.1016/j.fbio.2023.102860
25. Tokiwa, Y., & Ugwu, C. U. (2007). Biotechnological production of (R)-3-hydroxybutyric acid monomer. *Journal of Biotechnology*, *132*, *264-272*.
26. Tokiwa, Y., Calabia, B. P., Ugwu, U., & Aiba, S. (2008). Biological production of functional chemicals from renewable resources. *Canadian Journal of Chemistry*, *86*, *548-555*.
27. Tokiwa, Y., Calabia, B., Ugwu, U., & Aiba, S. (2009). Biodegradability of plastics. *International Journal of Molecular Sciences*, *10*, *3722-3742*. doi: 10.3390/ijms10093722
28. Bai, X., Dinkla, I. J. T., & Muyzer, G. (2022). Microbial ecology of biofiltration used for producing safe drinking water. *Applied Microbiology and Biotechnology*, *106*(13-16), *4813-4829*. doi: 10.1007/s00253-022-12013-x
29. Rolewicz-Kalinska, A., Lelicinska-Serafin, K., & Manczarski, P. (2021). Volatile organic compounds, ammonia and hydrogen sulphide removal using a two-stage membrane biofiltration process. *Chemical Engineering Research and Design*, *165*, *69-80*.
30. Ekpan, F. M., Ori, M. O., Samuel, H. S., & Egwuatu, O. P. (2024). Emerging technologies for eco-friendly production of bioethanol from lignocellulosic waste materials. *Eurasian Journal of Science and Technology*, *4*(3), *179-194*. doi: 10.48309/ejst.2024.429106.1119
31. Lee, J., & Marrocchi, A. (2024). Advances in green chemistry and engineering. *Scientific Reports*, *14*, *3133*. doi: 10.1038/s41598-024-53594-z
32. Ghosh, S., Sinha, J. K., Ghosh, S., Vashisth, K., Han, S., & Bhaskar, R. (2023). Microplastics as an emerging threat to the global environment and human health. *Sustainability*, *15*(14), *10821*. doi: 10.3390/su151410821
33. Samuel, H. S., & Etim, E. E. (2023). Water quality evaluation of Abakpa River in Ogoja Local Government Area Cross River State. *Medical & Analytical Chemistry International Journal*, *7*(2), *000186*. doi: 10.23880/macij-16000186
34. Calero, M., Godoy, V., Quesada, L., & Martín-Lara, M. Á. (2021). Green strategies for microplastics reduction. *Current Opinion in Green and Sustainable Chemistry*, *28*, *100442*. doi: 10.1016/j.cogsc.2020.100442

35. Ori, M., Ekpan, F., Samuel, H., & Egwuatu, O. (2024). Emerging co-cultivation strategies for microalgal biomass and biodiesel production. *Progress in Chemical and Biochemical Research*, *7*(2), *198-224*. doi: 10.48309/pcbr.2024.425990.1317