Asian Journal of
Science, Technology, Engineering, and Art

e-ISSN: 3025-4507
p-ISSN: 3025-5287
Index: Harvard, Boston, Sydney University, Dimensions, Lens, Scilit, Semantic, Google, etc

https://doi.org/10.58578/AJSTEA.v3i3.5409

Assessment, Characterization, and Bioprocessing of E-Waste Plastics in the Environment

Taiwo Bakare-Abidola & Jelil Olaoye
Georgia Southern University, Georgia, USA
bakareabidolataiwo@gmail.com; oolaoyeolamidee@gmail.com

Article Info:

Submitted:	Revised:	Accepted:	Published:
Mar 14, 2025	Mar 29, 2025	Apr 10, 2025	Apr 15, 2025

Abstract

E-waste plastics pose significant environmental and health challenges due to their complex composition and the harmful chemicals they contain. The improper disposal of these materials through methods like landfilling and incineration exacerbates their environmental impact. This review explores the assessment, characterization, and bioprocessing of e-waste plastics, focusing on their chemical properties, degradation mechanisms, and potential biotechnological solutions. Emerging technologies such as microbial degradation and enzymatic breakdown offer promising alternatives for the efficient recycling of these materials, potentially reducing their environmental footprint. The integration of these biotechnological approaches within circular economy models could provide a sustainable solution for managing plastic waste. However, challenges related to scalability, toxicity, and the economic viability of these solutions remain. Additionally, effective policy frameworks and regulations are crucial in guiding the sustainable management of e-waste plastics. This review also discusses future research directions, emphasizing the need for optimized bioremediation techniques and the importance of

AJSTEA Journal is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License

strengthening international policies to address the growing issue of e-waste plastics.

Keywords: E-Waste Plastics, Bioprocessing, Microbial Degradation, Enzymatic Breakdown, Circular Economy, Policy Frameworks, Plastic Recycling, Environmental Impact

Introduction

The rapid growth of electronic waste (e-waste) has become a significant global environmental challenge, particularly in terms of the plastics that constitute a major portion of e-waste. E-waste refers to discarded electronic devices, such as smartphones, computers, and home appliances, which contain hazardous materials, including plastics, metals, and chemicals (Baldé et al., 2017). Plastics, in particular, present substantial difficulties in recycling and disposal due to their durability, non-biodegradability, and potential to release harmful substances such as heavy metals and flame retardants into the environment (Gupta & Kaur, 2020). The improper management of e-waste leads to environmental contamination, health risks to humans and wildlife, and the loss of valuable resources that could otherwise be recovered through recycling processes (Borga et al., 2019). Plastic components in e-waste are mainly composed of high-density polyethylene (HDPE), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), and polystyrene, which are difficult to degrade and often accumulate in landfills (Zhao et al., 2020). While conventional methods such as incineration and mechanical recycling are widely used, they pose significant environmental risks, including air pollution and the release of toxic compounds (Muthu et al., 2020). Therefore, there is a growing need for alternative solutions that can efficiently address the environmental impact of e-waste plastics. Bioprocessing, which involves the use of biological agents such as bacteria, fungi, and enzymes to break down plastic waste, has emerged as a promising solution to mitigate the environmental burden posed by e-waste plastics (Shah et al., 2021). This approach leverages the ability of certain microorganisms to degrade complex plastic polymers into simpler compounds, offering a potential pathway to recycling plastics into useful products or reducing their environmental impact (Tian et al., 2021). Recent studies have shown that microbial and enzymatic degradation processes are not only effective but may offer more sustainable and environmentally friendly alternatives to conventional plastic recycling

techniques (Zhang et al., 2019). Despite these advances, challenges remain in scaling bioprocessing techniques to handle the large volumes of e-waste plastics generated globally (Yu et al., 2022).

This review aims to assess and characterize e-waste plastics, exploring the role of bioprocessing in their treatment and recycling. By examining the current state of research in this area, we seek to identify key trends, challenges, and opportunities for improving the sustainability of e-waste plastic management.

Assessment of E-Waste Plastics

Composition of E-Waste Plastics

E-waste plastics are diverse in composition, as they come from a wide range of electronic devices, each containing different types of plastic materials. The most commonly found plastics in e-waste include polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), polystyrene (PS), polycarbonate (PC), and low-density polyethylene (LDPE) (Zhao et al., 2020). These plastics are used due to their durability, low cost, and ease of molding into complex shapes, making them suitable for various components like casings, wires, and internal structures.

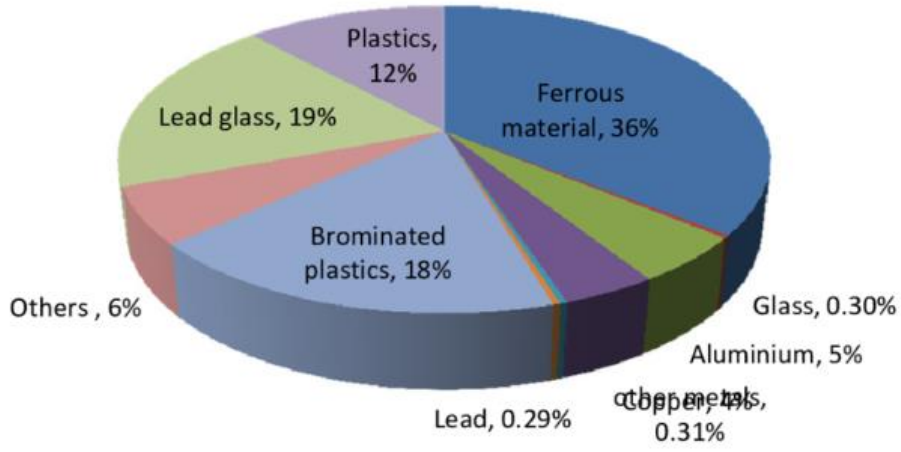


Figure 1: *Materials composition of E waste plastics*

Polyvinyl chloride (PVC) is widely used in insulation for wires and cables, and its plasticized form is often used in casing for various electronic devices. PVC is highly resistant to environmental degradation but releases toxic dioxins and phthalates when burned or improperly disposed of (Borga et al., 2019).

Acrylonitrile butadiene styrene (ABS) is another common plastic used in e-waste, particularly in computer and TV casings. ABS is tough and can resist impacts, but it is not biodegradable and contributes to persistent plastic waste (Gupta & Kaur, 2020).

Polystyrene (PS), often found in packaging, is a lightweight, rigid plastic that is easily broken into small particles, leading to environmental dispersion. PS is highly difficult to recycle and poses significant environmental hazards when it enters ecosystems (Muthu et al., 2020).

These plastics pose a considerable challenge to recycling and disposal because they often contain harmful additives like flame retardants and plasticizers, which can be toxic to both the environment and human health.

Environmental and Health Impacts

The environmental and health impacts of e-waste plastics are significant due to the release of hazardous chemicals during degradation. When exposed to sunlight, heat, or mechanical processes like shredding, e-waste plastics can leach chemicals into the surrounding environment. For example, PVC releases harmful substances such as dioxins, phthalates, and heavy metals (like lead and cadmium) when exposed to heat during incineration or improper disposal (Borga et al., 2019). These substances can contaminate soil, water, and air, leading to long-term environmental pollution. In addition, polystyrene and ABS plastics, when improperly disposed of or incinerated, release toxic byproducts, including styrene, which has been classified as a possible human carcinogen (Gupta & Kaur, 2020). The persistence of these plastics in the environment is another concern, as they do not biodegrade easily and accumulate in landfills, where they continue to leach harmful substances into surrounding ecosystems over time.

The human health impacts are also considerable. Long-term exposure to chemicals such as phthalates and heavy metals can cause neurological disorders, reproductive toxicity, and cancer (Zhao et al., 2020). Moreover, workers in e-waste recycling facilities are at a heightened risk due to direct exposure to these toxic substances, often without proper safety measures (Muthu et al., 2020).

E-Waste Plastic Collection and Disposal Methods

Current methods for managing e-waste plastics generally include landfilling, incineration, and recycling, each with varying degrees of environmental impact.

Landfilling is one of the most common methods for disposing of e-waste plastics. However, it leads to the accumulation of non-biodegradable plastics in the environment, which takes hundreds to thousands of years to degrade (Zhao et al., 2020). Landfills also pose a risk of leaching hazardous chemicals into groundwater and soil, particularly when plastics are exposed to water or heat.

Incineration is another common disposal method, especially in regions where e-waste is not properly recycled. This process involves burning plastics at high temperatures, which can reduce the volume of waste but leads to the release of toxic gases such as dioxins, furans, and particulate matter (Borga et al., 2019). Incineration is often considered a less favorable option due to its environmental and health risks.

Recycling is the preferred method for managing e-waste plastics, but it is still limited by technological and economic challenges. While some e-waste plastics can be mechanically separated and reused, many types of plastics, particularly those mixed with other materials like metals and glass, are difficult to recycle effectively (Gupta & Kaur, 2020). Furthermore, recycling rates are often low in many developing countries due to a lack of proper infrastructure and awareness.

Assessment of Current Recycling Technologies

Recycling technologies for e-waste plastics have made some progress, but there remain significant limitations in their effectiveness. Mechanical recycling is the most commonly used technology, which involves shredding and sorting plastics based on their types. However, this method faces challenges in dealing with mixed plastics, contaminants, and the degradation of plastic properties during the recycling process (Muthu et al., 2020).

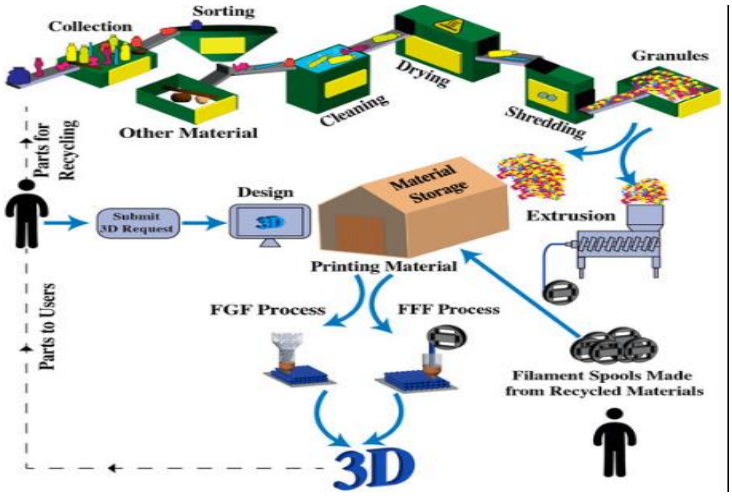


Figure 2: Waste (Plastic) recycling

Another recycling approach is chemical recycling, which aims to break down plastics into their monomeric components for reuse in manufacturing. While chemical recycling holds promise, it is still in the experimental stages for many e-waste plastics, and its high energy requirements and costs remain significant barriers (Gupta & Kaur, 2020).

A more recent approach, biological recycling, uses microorganisms, fungi, or enzymes to degrade plastics. This technique is seen as an environmentally friendly alternative to conventional methods and has shown success in laboratory settings for degrading certain types of plastics such as PET (polyethylene terephthalate) and polystyrene (Shah et al., 2021). However, challenges in scalability and efficiency remain, and more research is needed to optimize bioprocessing for e-waste plastics on an industrial scale (Zhao et al., 2020). Despite these advances, the current recycling technologies remain insufficient to deal with the vast quantities of e-waste plastics generated globally. Effective solutions will require innovations in both technology and policy, with a focus on improving recycling infrastructure, developing more efficient biotechnological methods, and promoting global standards for e-waste management (Yu et al., 2022).

Characterization of E-Waste Plastics

Physical and Chemical Properties

The characterization of e-waste plastics is a crucial step in understanding their behavior in the environment and assessing their recyclability and potential toxicity. Various analytical techniques are employed to examine the physical and chemical properties of e-waste plastics. Fourier-transform infrared spectroscopy (FTIR) is one of the most widely used methods for identifying the chemical bonds and molecular structures of plastics. FTIR helps in detecting specific functional groups and understanding the polymer composition of e-waste plastics, such as PVC, ABS, and polystyrene, which may vary significantly depending on the source of the e-waste (Liu et al., 2021).

Ultraviolet-visible (UV-Vis) spectroscopy is another powerful technique used to investigate the optical properties of e-waste plastics. UV-Vis spectroscopy can provide information on the absorption spectra of plastics, helping to determine their stability under different environmental conditions (Li et al., 2020). This technique is particularly useful for studying the degradation of e-waste plastics when exposed to sunlight or UV radiation, which is a major factor influencing their environmental persistence.

Chromatographic techniques, such as gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC), are utilized to separate and identify small molecules, additives, and contaminants present in e-waste plastics. These methods are effective in detecting hazardous substances, including phthalates, flame retardants, and heavy metals, which are often added during the manufacturing process to improve the plastic's properties (Liu et al., 2021). Additionally, thermogravimetric analysis (TGA) is employed to assess the thermal stability and composition of e-waste plastics by measuring weight changes as the material is heated. This technique provides valuable insights into the decomposition temperature, volatility, and combustion behavior of the plastics (Zhao et al., 2020).

These characterization techniques are essential for identifying the specific types of plastics present in e-waste and understanding their chemical makeup, which in turn influences their environmental fate and the effectiveness of recycling processes.

Degradation and Chemical Changes

E-waste plastics undergo complex chemical changes when exposed to environmental factors such as sunlight, heat, moisture, and microbial activity. The degradation of these plastics is influenced by factors such as the type of plastic, its chemical additives, and the environmental conditions to which it is exposed. For example, PVC is known to degrade under UV radiation, releasing toxic substances like hydrochloric acid and dioxins, which can be harmful to both the environment and human health (Borga et al., 2019). The degradation of ABS plastics is often slower due to their more stable chemical structure, but over time, they can release styrene monomers, which are toxic and persistent in the environment (Gupta & Kaur, 2020).

In general, the degradation of e-waste plastics in the environment involves the breakdown of polymer chains due to photodegradation, thermal degradation, and microbial processes. Photodegradation, caused by exposure to UV radiation, leads to the breaking of chemical bonds in the plastic, producing free radicals and leading to the formation of smaller fragments (Zhao et al., 2020). Over time, these smaller fragments may be further degraded by microbial activity, although plastics are generally resistant to complete biodegradation. In the case of polystyrene and HDPE, the degradation process can be slow, lasting years or even decades, depending on environmental conditions.

Chemical changes during the degradation of e-waste plastics can result in the formation of hazardous substances such as bisphenol A (BPA), phthalates, and heavy metals like lead and cadmium, which are often incorporated as additives or contaminants (Li et al., 2020). These chemicals can leach into soil and water, contributing to pollution and posing serious risks to human and ecological health.

Impact on Ecosystems

E-waste plastics, due to their persistence and toxicity, pose significant risks to ecosystems when improperly disposed of or not properly recycled. Different types of e-waste plastics interact with various environmental systems in distinct ways, affecting soil, water, and air quality.

In soil ecosystems, e-waste plastics can alter the structure and composition of soil by introducing microplastics and harmful chemicals. When e-waste plastics decompose in landfills or in open environments, they can release substances like lead, cadmium, and mercury, which can contaminate soil and affect soil fertility and plant growth (Liu et al., 2021). Microplastics, often formed during the physical breakdown of plastics, can be ingested by soil organisms, disrupting their physiology and impacting biodiversity.

In aquatic ecosystems, e-waste plastics can have disastrous effects, especially when they enter water bodies through runoff or improper disposal. Polystyrene and PVC plastics, when exposed to water, can break into small particles that are easily ingested by aquatic life. These microplastics can enter the food chain, affecting species diversity and ecosystem health. The leaching of toxic chemicals from plastics, such as phthalates and styrene, can cause disruption to the endocrine systems of aquatic organisms, leading to reproductive issues and population declines (Borga et al., 2019).

Finally, in the air, burning or incinerating e-waste plastics releases harmful substances like dioxins, furans, and particulate matter, which are detrimental to both environmental and human health. These airborne pollutants can travel long distances, contaminating large areas and impacting both terrestrial and aquatic environments. Incineration of e-waste plastics, particularly PVC and ABS, results in the formation of toxic byproducts, including hydrochloric acid and carbon monoxide, which can persist in the atmosphere and pose long-term health risks (Gupta & Kaur, 2020).

The impact of e-waste plastics on ecosystems is a growing concern, particularly as the volume of electronic waste continues to rise globally. Effective management and recycling of these materials are essential to mitigate their environmental and health impacts.

Discussion

Bioprocessing of E-Waste Plastics

Microbial Degradation

Microbial degradation is a natural process in which microorganisms, particularly bacteria and fungi, break down complex polymers into simpler, more environmentally friendly substances. Several studies have highlighted the potential of various microbial species to degrade plastics found in e-waste. Bacteria such as *Ideonella sakaiensis*, which can degrade PET (polyethylene terephthalate), have gained significant attention for their role in plastic bioremediation (Yoshida et al., 2016). These bacteria utilize enzymes, including PETase, to hydrolyze PET into its monomers, which are further degraded through microbial metabolism. Similarly, fungi like *Aspergillus niger* have demonstrated the ability to degrade polystyrene, breaking it down into smaller fragments that are more easily assimilated (Shah et al., 2020). The mechanisms behind these processes typically involve the secretion of specific enzymes that attack the polymer's structure, initiating depolymerization and eventually converting the material into simpler compounds.

While microbial degradation shows promise, it faces significant challenges due to the recalcitrant nature of many plastics used in e-waste. The slow rate of degradation and the need for specialized conditions (e.g., temperature, pH, and oxygen availability) can hinder the effectiveness of natural microbial processes in large-scale applications (Praveen et al., 2021). Nevertheless, with ongoing research, microbial strains are being isolated and optimized to enhance degradation efficiency and plastic processing times.

Enzymatic Breakdown

Enzymatic breakdown of e-waste plastics has become a focal point for bioremediation research, with the goal of harnessing naturally occurring or engineered enzymes to degrade complex plastics more efficiently. Enzymes such as lipases, laccases, and cutinases have been identified for their ability to break down various polymers, including those found in e-waste. For instance, polyhydroxyalkanoates (PHA), a biodegradable plastic, can be

produced by certain microorganisms as a sustainable alternative to petrochemical-based plastics (Lee et al., 2020). These biocatalysts, produced by bacteria and fungi, are able to hydrolyze plastics into monomers or smaller oligomers that can be further metabolized by microorganisms.

Recent advancements in enzymatic plastic degradation have focused on genetically engineering microbial enzymes to enhance their activity and stability under harsher conditions typically found in waste environments (Nikel et al., 2019). Additionally, efforts have been made to optimize enzyme production processes, making them more cost-effective and scalable for industrial applications. The use of enzyme-based bioremediation could lead to the development of cleaner, more efficient methods for breaking down e-waste plastics, potentially creating useful byproducts such as biofuels or raw materials for the production of biodegradable plastics.

Biotechnological Approaches for Plastic Recycling

Biotechnological innovations are rapidly advancing in the field of plastic recycling, particularly in converting e-waste plastics into useful products such as biofuels, biodegradable materials, or other valuable chemicals. One promising approach is the conversion of plastics like polystyrene and polyethylene into biofuels through microbial fermentation processes. Certain bacteria and yeasts can metabolize plastic monomers into bioethanol or biobutanol, providing an alternative to fossil fuels and helping to reduce plastic waste (Klein et al., 2020). Another example is the production of biodegradable materials through biotechnological processes, where microorganisms convert e-waste plastics into biopolymers such as PHA or polyhydroxybutyrate (PHB), which can be used in various applications, including packaging and agricultural films (Koller et al., 2021).

These biotechnological processes are still in the early stages of development but hold significant promise for mitigating the environmental impacts of e-waste plastics. The conversion of waste plastics into valuable products not only provides a potential solution for plastic disposal but also supports the development of a circular economy by creating renewable materials that can be reused and repurposed.

Challenges and Opportunities

Despite the potential benefits of bioprocessing e-waste plastics, several challenges remain that hinder the widespread application of these technologies. One major challenge is the slow degradation rate of plastics, especially those with highly stable chemical structures

such as PVC and polystyrene. The time required for microbial or enzymatic degradation to effectively reduce plastic volumes to environmentally acceptable levels is often prohibitive for large-scale waste management efforts (Praveen et al., 2021).

Moreover, the toxicity of certain chemicals present in e-waste plastics, such as heavy metals (e.g., lead, cadmium) and flame retardants, can interfere with the metabolic activity of microorganisms and enzymes, inhibiting the bioprocessing of these materials (Yoshida et al., 2016). Addressing these challenges will require advances in the genetic engineering of microorganisms to enhance their resistance to toxic substances and their ability to degrade more recalcitrant plastics.

Opportunities exist in the form of genetically engineered microorganisms and enzyme optimization to increase the efficiency and speed of plastic degradation. Furthermore, advancements in synthetic biology could enable the design of tailored enzymes or microbes capable of breaking down a wider range of plastics, even those currently resistant to degradation (Nikel et al., 2019). By overcoming these technical barriers, bioprocessing technologies could provide a sustainable and efficient method for recycling e-waste plastics and reducing the environmental burden associated with plastic pollution.

Future Directions and Trends in E-Waste Plastic Management

Innovative Biotechnological Solutions

The management of e-waste plastics is at a critical juncture, as current recycling methods are often inadequate to handle the vast and growing amounts of plastic waste. As the global concern regarding plastic pollution intensifies, the development of innovative biotechnological solutions to treat e-waste plastics is gaining significant momentum. The integration of synthetic biology and genetic engineering into the bioremediation of plastics has emerged as a promising frontier in this domain.

One of the most exciting areas of research is the genetic modification of microorganisms to enhance their ability to degrade plastic materials commonly found in e-waste, such as PVC, polystyrene, and polyethylene terephthalate (PET). Advances in genetically engineered bacteria have already demonstrated remarkable success in breaking down synthetic polymers. For instance, *Ideonella sakaiensis*, a bacterium capable of degrading PET, has been modified to improve its degradation efficiency (Yoshida et al., 2016). By

optimizing the enzymes produced by such microbes, researchers are working towards creating more efficient strains capable of handling a broader range of plastics found in e-waste.

Additionally, synthetic biology is being leveraged to design entirely new metabolic pathways in microorganisms that allow them to break down plastics in more efficient and environmentally benign ways. Synthetic pathways are being engineered in microorganisms to produce novel enzymes or catalyze the conversion of plastic waste into valuable byproducts such as biofuels, biopolymers, or biodegradable materials. This innovation is not only important for plastic waste management but also has the potential to support the circular economy by creating a closed-loop system in which e-waste plastics are converted back into useful resources (Nikel et al., 2019). These advances could help overcome some of the limitations posed by traditional mechanical and chemical recycling processes, offering a more sustainable and environmentally friendly solution.

Moreover, enzymatic degradation is being explored as a method of breaking down plastics more efficiently. The production of polyhydroxyalkanoates (PHA), biodegradable plastics produced by bacteria, is a potential solution that not only addresses the degradation of e-waste plastics but also creates valuable, sustainable alternatives to petroleum-based plastics (Koller et al., 2021). Advances in biotechnology could see these approaches integrated into industrial-scale applications for recycling plastic waste, potentially changing the way plastic waste is handled globally.

Circular Economy and Sustainability

The concept of the circular economy is integral to addressing the sustainability challenges posed by e-waste plastics. In a circular economy, the focus shifts from a linear model of "take, make, dispose" to a more sustainable, closed-loop system where materials are continuously reused, remanufactured, or recycled to minimize waste and reduce environmental impact. In the context of e-waste plastics, this model could transform plastic waste management by creating a system where plastics are reused, recycled, or bioprocessed into valuable products rather than being discarded into landfills or incinerated.

Integrating e-waste plastics into a circular economy is feasible with the help of innovative biotechnological solutions. For instance, as discussed earlier, genetically modified

organisms and engineered enzymes could be used to break down plastic waste into reusable monomers, which can then be repurposed for manufacturing new products, including biodegradable plastics. This process creates a closed-loop where plastics from e-waste are not only recycled but also regenerated into new, functional materials, contributing to a more sustainable waste management cycle (Klein et al., 2020).

Another promising approach is the use of biological upcycling, a process where e-waste plastics are converted into higher-value products such as bioplastics, biofuels, or chemical precursors for pharmaceuticals. This upcycling approach supports the circular economy by creating new products from waste, while also reducing the demand for virgin plastic production, thus decreasing the associated environmental and resource extraction impacts (Praveen et al., 2021).

The biodegradability of certain bioplastics produced from e-waste could further support sustainability efforts. By reducing the persistence of plastic waste in the environment, biodegradable plastics offer an important advantage over conventional, non-degradable plastics, aligning with environmental sustainability goals. The potential for developing a closed-loop system where e-waste plastics are not only recycled but also biodegraded in environmentally friendly ways represents a significant step toward achieving sustainability in plastic waste management.

Policy and Regulation

As innovative biotechnological solutions are developed to manage e-waste plastics, the role of policy and regulation becomes increasingly important in shaping the future of plastic waste management. National and international policies must evolve to facilitate the widespread adoption of these new technologies while ensuring that they are implemented safely and effectively. A key area of policy development is the Basel Convention, an international treaty that governs the movement of hazardous wastes across borders. The Basel Convention aims to reduce the transboundary movement of e-waste and ensure that it is disposed of or treated in an environmentally sound manner. However, as e-waste plastics are increasingly recognized as a significant environmental threat, the Basel Convention may need to be expanded to include more specific regulations for plastic waste, including guidelines for biotechnological treatment methods.

In addition, Extended Producer Responsibility (EPR) is a policy approach that has gained traction in many countries, holding producers accountable for the disposal of products at

the end of their lifecycle. EPR schemes can encourage manufacturers to design products with easier recyclability, better recyclability technologies, and to take responsibility for recycling plastic waste, including e-waste plastics. By making manufacturers responsible for the entire lifecycle of their products, EPR schemes could encourage companies to adopt more sustainable production methods and invest in biotechnological innovations that improve the recycling of e-waste plastics.

At the global level, international agreements such as the OECD's Framework on E-Waste and the European Union's Circular Economy Action Plan are important steps toward regulating e-waste plastic management. These frameworks promote the development of sustainable recycling technologies and the adoption of a circular economy approach to plastics. The regulation of e-waste plastics at the international level can encourage collaboration between countries, ensure that the most effective and sustainable recycling methods are shared globally, and set a global standard for managing e-waste plastic pollution.

Challenges and Opportunities

While significant advancements have been made in the biotechnological processing of e-waste plastics, several challenges remain. One of the key barriers is the scalability of these biotechnological solutions. Many of the innovative approaches for degrading e-waste plastics are still in the laboratory or pilot stages, and scaling them up to industrial levels will require substantial investment and infrastructure. In addition, the economic viability of biotechnological methods, including genetically modified microorganisms and enzyme-based recycling, needs to be carefully assessed to ensure they can compete with traditional mechanical and chemical recycling processes.

Another challenge lies in the toxicity of certain e-waste plastics, which may contain heavy metals, flame retardants, and other harmful additives. These toxic substances can inhibit the activity of microorganisms and enzymes, reducing the efficiency of biotechnological processes. Furthermore, their presence could pose risks to human health and the environment if not properly managed. Therefore, ongoing research is necessary to understand how to effectively treat these toxic materials and minimize their impact during bioremediation processes (Yoshida et al., 2016).

Despite these challenges, opportunities abound for improving the biotechnological treatment of e-waste plastics. The continuous evolution of genetic engineering and

synthetic biology offers promising solutions for enhancing the efficiency of microbial degradation. Advances in metabolic engineering could lead to the development of microorganisms that can degrade a wider range of plastics, including more recalcitrant polymers. Additionally, collaborative efforts between governments, industries, and academic researchers could accelerate the adoption of circular economy principles and biotechnological innovations, fostering a more sustainable and environmentally friendly approach to managing e-waste plastics.

Conclusion

This review highlights the challenges and opportunities in addressing e-waste plastics, emphasizing their complex composition and harmful environmental impacts. While traditional disposal methods like landfilling and incineration are insufficient, emerging biotechnological solutions, such as microbial and enzymatic degradation, offer promising alternatives for plastic recycling and waste management. However, challenges such as scalability, toxicity, and economic viability remain. To address these, future research should focus on optimizing biotechnological processes, enhancing the efficiency of degradation, and scaling these solutions for industrial use. Additionally, integrating circular economy models and strengthening regulatory frameworks, including international policies like the Basel Convention and Extended Producer Responsibility (EPR), are essential for promoting sustainable plastic waste management.

References

Baldé, C. P., Wang, F., Kuehr, R., & Huisman, J. (2017). *The global e-waste monitor 2017: Quantities, flows, and the circular economy potential.* United Nations University.
Borga, P., Marušić, A., & Hötzl, H. (2019).
Environmental risks of e-waste plastics and methods for effective management. *Environmental Science and Pollution Research, 26*(3), 2049-2061. https://doi.org/10.1007/s11356-018-3561-4
Gupta, D., & Kaur, S. (2020).
Assessment of environmental threats posed by e-waste plastics: Challenges and solutions. *Journal of Environmental Management, 266*, 110520.
Muthu, S. S., Li, Y., & Choi, D. (2020). *Sustainable recycling of e-waste plastics: Challenges and future directions*. Springer.
Shah, M. P., Hegde, P., & Gokhale, A. A. (2021). Biodegradation of e-waste plastics: Microbial and enzymatic approaches. *Biotechnology Advances, 44*, 107637.

Tian, W., Yu, Z., & Zhang, X. (2021). Microbial degradation of e-waste plastics and the potential for bioprocessing. *Environmental Pollution, 268*, 115551.

Zhang, Y., Li, Q., & Wang, S. (2019). Advances in the bioremediation of e-waste plastics. *Environmental Science & Technology, 53*(18), 10950-10959.

Zhao, Q., Zheng, L., & Wu, J. (2020). Characterization and environmental impact of plastics in e-waste: A review. *Science of the Total Environment, 735*, 139487.

Yu, Y., Ren, Z., & Zhang, W. (2022). Scaling bioprocessing techniques for e-waste plastic recycling: Challenges and future perspectives. *Journal of Hazardous Materials, 430*, 128547.

Borga, P., Marušić, A., & Hötzl, H. (2019). Environmental risks of e-waste plastics and methods for effective management. *Environmental Science and Pollution Research, 26*(3), 2049-2061.

Gupta, D., & Kaur, S. (2020). Assessment of environmental threats posed by e-waste plastics: Challenges and solutions. *Journal of Environmental Management, 266*, 110520.

Li, X., Zhang, S., & Zhao, S. (2020). Photodegradation of e-waste plastics under UV radiation: A study on the formation of chemical contaminants. *Environmental Pollution, 267*, 115639.

Liu, X., Zhang, H., & Wang, T. (2021). Analytical techniques for the identification and characterization of e-waste plastics. *Waste Management, 122*, 69-80.

Zhao, Q., Zheng, L., & Wu, J. (2020). Characterization and environmental impact of plastics in e-waste: A review. *Science of the Total Environment, 735*, 139487.

Borga, P., Marušić, A., & Hötzl, H. (2019). Environmental risks of e-waste plastics and methods for effective management. *Environmental Science and Pollution Research, 26*(3), 2049-2061.

Gupta, D., & Kaur, S. (2020). Assessment of environmental threats posed by e-waste plastics: Challenges and solutions. *Journal of Environmental Management, 266*, 110520.

Muthu, S. S., Li, Y., & Choi, D. (2020). *Sustainable recycling of e-waste plastics: Challenges and future directions*. Springer.

Shah, M. P., Hegde, P., & Gokhale, A. A. (2021). Biodegradation of e-waste plastics: Microbial and enzymatic approaches. *Biotechnology Advances, 44*, 107637.

Yu, Y., Ren, Z., & Zhang, W. (2022). Scaling bioprocessing techniques for e-waste plastic recycling: Challenges and future perspectives. *Journal of Hazardous Materials, 430*, 128547.

Zhao, Q., Zheng, L., & Wu, J. (2020). Characterization and environmental impact of plastics in e-waste: A review. *Science of the Total Environment, 735*, 139487. https://doi.org/10.1016/j.scitotenv.2020.139487

Klein, A. T., Alves, L. D., & Machado, A. A. S. (2020). Microbial conversion of plastic waste into biofuels: Advances and challenges. *Bioresource Technology, 299*, 122585.

Koller, M., Szentirmai, A., & Rechberger, H. (2021). Biotechnological recycling of plastics for sustainable polymer production. *Journal of Biotechnology, 332*, 85-94.

Nikel, P. I., Chavarría, M., & de Lorenzo, V. (2019). Biodegradation of plastics: New frontiers in bioremediation technologies. *Current Opinion in Biotechnology, 55*, 34-42.

Praveen, K. P., Rathi, P. S., & Soni, M. (2021). Challenges in microbial degradation of plastics from e-waste. *Environmental Pollution, 275*, 116586.

Yoshida, S., Hiraga, K., & Takeuchi, M. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science, 351*(6278), 1196-1199.

Klein, A. T., Alves, L. D., & Machado, A. A. S. (2020). Microbial conversion of plastic waste into biofuels: Advances and challenges. *Bioresource Technology, 299*, 122585.

Koller, M., Szentirmai, A., & Rechberger, H. (2021). Biotechnological recycling of plastics for sustainable polymer production. *Journal of Biotechnology, 332*, 85-94. Lee, S. Y., ho, H. H., & Kim, H. J. (2020). Polyhydroxyalkanoates (PHA) production from plastic waste: A sustainable biotechnological approach. *Renewable and Sustainable Energy Reviews, 130*, 109936.

Nikel, P. I., Chavarría, M., & de Lorenzo, V. (2019). Biodegradation of plastics: New frontiers in bioremediation technologies. *Current Opinion in Biotechnology, 55*, 34-42.

Praveen, K. P., Rathi, P. S., & Soni, M. (2021). Challenges in microbial degradation of plastics from e-waste. *Environmental Pollution, 275*, 116586.

Shah, M. A., Sharma, P. M., & Yadav, K. (2020). Fungal degradation of polystyrene: Insights into microbial plastic bioremediation. *Microbial Biotechnology, 13*(1), 130-141.

Yoshida, S., Hiraga, K., & Takeuchi, M. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science, 351*(6278), 1196-1199.