STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 6, 2025
DOI (Journal): 10.37591/JoPC

Review JoPC

Management of Nanoparticles E-Waste to Energy Conversion for Sustainability with Composite Substances

Nimmi Agarwal[1], Parul Saxena[2,*]

Abstract

Changing the nanoparticles in e-waste streams could give us greater control as middlemen and a big possibility to find better ways to save energy and protect the environment. Nanomaterials are being used more and more in the electronics industry, and they leave behind harmful waste that stays in the environment. Using nanoparticles to turn e-waste into electricity will fix these concerns and make toxicity a part of the circular economy. The nanoparticles in outdated electrical equipment can be kept for eventual use or transformed into something very safe using advanced thermal, chemical, and biological processes. After that, the leftover stuff is used to make power or heat. This two-way plan not only stops land-dumping, but it also tackles two huge problems: it protects the environment and makes resources usable. Nanotechnology can help make waste valorization more effective, which can lead to better recovery methods and cleaner energy outputs. Countries that are becoming more industrialized can also acquire energy from decentralized waste-to-energy systems that use nanoparticle treatment. This is in accordance with the global aims of sustainable development. But problems like high operational expenses, gaps in the law, and the risk of nanoparticles being released during treatment keep showing how important it is to have strict rules and new ways to handle things. This combination strategy can turn a dangerous waste stream into a helpful resource for the future. It can also make protecting natural resources, energy safety, and the environment more stronger.

Keywords: Nanoparticles, E-waste management, waste-to-energy, sustainability, composite substance

INTRODUCTION

In 2023, electronic trash is one of the worst things for the environment in the age of the Internet. Since then, more than 53 million metric tons have been made every year, making it the fastest-growing waste stream on Earth. Reports suggest that the amount of e-waste made has gone increasing lately because technology changes swiftly and products don't last as long [1]. This phenomena also presents unique risks to the environment and big opportunities for long-term innovation. One of the hardest difficulties to overcome in the sophisticated world of engineering waste is how to get rid of nanoparticles that are stuck in electronics.

These particles are bad for the environment and people's health in different ways, but they might also help new technologies that turn trash into energy [2]. Not only is it a new way to trade in e-waste that is full of nanoparticles that can be used as energy sources, It demonstrates a whole new way of living, one that moves away from the old-fashioned linear way of life and toward the recycle and reuse attitude that the whole-hearted are advocating for. Nanomaterials are a blend of different materials that are used in modern electronics. Silver nanoparticles

***Author for Correspondence**
Parul Saxena

[1]Associate Professor, Department of Management, Sharda University, Greater Noida, Uttar Pradesh, India
[2]Associate Professor, Department of Management, Sharda University, Greater Noida, Uttar Pradesh, India

Received Date: October 06, 2025
Accepted Date: November 01, 2025
Published Date: December 04, 2025

Citation: Nimmi Agarwal, Parul Saxena. Management of Nanoparticles E-Waste to Energy Conversion for Sustainability with Composite Substances. Journal of Polymer & Composites. 2025; 13(Special Issue 6): S1007–S1015p.

are employed in conductive inks, rare earth nanocrystals are used in permanent magnets, and metal oxide nanomaterials make up most of the sensors and semiconductor integrated circuits [3]. These nanoscale materials make gadgets work better and do more things, but their unique features and ability to move around in the environment make it tougher to deal with them as they reach the end of their useful life.

If you discard away these nanoparticles the incorrect way, such at a landfill or by burning them, they could change in ways that are impossible to predict and release harmful substances into the air, water, and ground. There is a lot of proof that not properly processing e-waste can harm the environment. Studies of recycling areas in big cities throughout the world have shown that these places have unusually high amounts of heavy metals, persistent organic pollutants, and nanoparticles. All of these results illustrate how vital it is to find innovative, safe ways to deal with engineering trash that has a lot of nanoparticles in it and make something useful out of these high-tech materials [4]. The idea of turning e-waste into energy is innovative and solves a lot of concerns with sustainability at the same time. This technique uses cutting-edge thermal, chemical, and biological technologies to turn outdated electronics into energy and obtain back useful micro and nano particles, just like traditional waste-to-energy technology [5–10].

Pyrolysis, gasification, and anaerobic digestion are some of the technologies that could be useful for dealing with e-waste. They can also create sustainable energy and have less of an impact on ecosystems in the area. Adding nanotechnology to waste-to-energy systems can make the verminderia even better [11]. Nanocatalysts in energy conversion have made things 20–30% more efficient and have even made it possible to fully recover resources, which is even better. This mix of making energy and getting resources back is exactly what a circular economy requires. It turns garbage into useful resources and reduces the need to mine for raw minerals.

RELEVANCE AND OBJECTIVE OF RESEARCH

Using nanoparticles to turn e-waste into electricity has a lot more long-term effects on sustainability than merely helping with waste management right now. They really do encompass everything from national security to protecting the environment to development [12–15]. As the world's need for rare earth elements is predicted to climb from 208,250 tons this year (2019) to 304,678 tons in 2050, it is becoming more and more vital to find ways to acquire them from trash. This is primarily because to electric cars and renewable energy sources. Engineered nanoscale ligands and nanoporous membranes are employed in a new generation of superior nanoparticle recovery technologies. These technologies can recover more than 80% of valuable metals and rare earths.

This means that mining operations that hurt the environment and contaminate it are not needed as much anymore. This strategy is also good for the economy since it will provide lucrative streams of materials that can pay for processing costs and create jobs in green technology. These technologies also help us reach our enormous goals for sustainability [16–25]. This is because they can help us get renewable energy, which we can utilize to make our environment less carbon-heavy, and they can help us reduce greenhouse gas emissions from mining and smelting. But to make this work, we will have to deal with a lot of challenges, like high operating expenses, holes in the rules, the chance that nanoparticles will be produced during conversion procedures, and the necessity for strong safety measures to safeguard both workers and the people who live nearby. To execute this job properly, you need a wide-ranging and cross-disciplinary framework that brings together the latest engineering solutions with in-depth environmental risk assessments, useful regulations, and cooperation from everyone in the value chain. If this idea works, it will turn an environmental concern into a building block for clean production and long-term management.

FUNDAMENTALS OF NANOPARTICLE E-WASTE MANAGEMENT WITH POLYMER AND COMPOSITES

Taking apart electronic parts and getting valuable metals out of obsolete printed circuit boards is nothing new. Because of well-planned steps, it's easy for us to get rid of copper, palladium, and other valuable metals. Nanoparticle recovery and polymer composite use to deal with e-waste is a novel technique to fix difficulties in China and while making things to sell abroad [26]. For instance, electronic waste, which is predicted to weigh 74.7 million tons in 2030, has a lot of metals and other components that can be converted into composite materials with high-value nanoparticles. Before processing Getting rid of Waste Printed Circuit Boards (WPCBs) is perhaps the most crucial step. WPCBs make up roughly 10% of all e-waste, however they have a lot of valuable metals in them, such as gold, silver, copper, and tin. Magnetic separations, crushing, and grinding are just a few of the tools that are increasingly widespread on production lines across the country. These are the optimal conditions for activities that recover valuable metals. Using biohydrometallurgy and sustainable synthesis procedures, green chemistry turns recovered metal ions into well-defined nanoparticles [27]. These processes use natural sources like plants and microorganisms. This job not only gets metal from scrap, but it also puts together important parts with polymer matrices. There is a lot of study that can be done on systems that use PP and PVC, for example. The findings indicate that as much as 25% of the polymeric e-waste derived from printed circuit boards can enhance the tensile modulus and flexural strength of composite materials. Surface modification and compatibilization techniques can change the non-metallic components of WPCBs, which make up around 60% of the board by weight, into composite materials that are worth more. Successful technologies turn e-waste straight into valuable nanomaterials that may be used right away. This makes e-waste useful. This approach fixes two difficulties at once: it can handle a lot of different kinds of garbage and is easy to get to for a lot of different purposes [28]. For example, laser ablation can be used to generate gold nanoparticles that are around 90% pure and have an average diameter of 100 nanometers. On the other hand, copper or copper oxide nanoparticles are good photocatalysts for cleaning up filthy water. For now, let's put off nano-shared nanocomposite materials. We need to build biodegradable polymer matrices to help us realize the aims of a circular economy. This offers me cellular materials that can be composted when they are no longer usable, are safe for people to use, and have mechanical properties that are similar to those of normal plastics. This combination of methods turned e-waste that was harmful into useful materials [29]. We can protect the environment and create jobs by encouraging the use of sustainable raw material recovery resources. These jobs could involve making super-tough nanocomposite materials that can be used in many different fields, including electronics, transportation, machinery manufacturing, construction, or cleanup business projects that are popular all over the world right now.

The basics of managing nanoparticle e-waste include a complicated mix of sorting technologies, health and environmental effects, and rules that all deal with the special problems that nanometer-scale electronic materials in old electronic devices create. Nanoparticles in e-waste are grouped by their size, shape, and how they are employed in electronic equipment. For instance, silver nanoparticles are used to generate conductive ink and coatings that kill bacteria. Rare earth nanomaterials are utilized in semiconductor parts and permanent magnets. These materials usually have sizes between 1 and 100 nm, and their properties are considerably different from those of their bulk counterparts. For example, they are more reactive, have a greater surface area-to-volume ratio, and can be moved around in the environment. You need advanced analytical tools like dynamic light scattering, electron microscopy, and X-ray photoelectron spectroscopy to measure their size, shape, and surface chemistry. This will help you see how they group together, which is a key sign of their environmental fate and how easy they are to access biologically.

It is important to recognize that some nanoparticles may be dangerous when they come into touch with them, such as when they are inhaled, eaten with contaminated food, or come into contact with products made with nanoparticles that contain heavy metals like lead. The more fish and mammals they kill in vast bodies of water, the more they hurt people. Dioxins that come from burning e-waste that runs downstream may be significantly more harmful because you come into direct contact with them instead of merely ingesting them. In conclusion, people play distinct roles in different areas, such the residences where they start their day and the e-waste landfills that take care of e-waste. When working out how much it costs to safeguard the environment, it's wrong to exclude both casual and work-related exposure. When e-waste is taken apart by machines, tiny bits of it are also released into the air. Of course, things that people do that lower thermal inversion are incredibly useful. But remember that instantaneous reaction and ultimate equilibrium are concepts from thermodynamics that explain what happens when things happen at the same time. But if you look closely at this process, you can see both paths between living things and things that aren't alive. It also displays how the treatment works, like the balance of dimensions in the reaction media or the level among layers where reactants are kept.

The criteria for getting rid of nanoparticle trash are still not clear, and the current system can't detect all the many features and risks of nanoparticles. There are no explicit laws for nanoproducts and garbage that incorporates manufactured nanomaterials. This means that there is a large gap in protection and oversight. The WHO, UNEP, and OECD are some of the international groups that have developed regulations and proposals concerning how safe nanoparticles are. But not all countries implement these principles in the same way. The REACH law in the EU specifies that substances must be examined for dangers. But for nanowastes, restrictions are based on traditional bulk materials, which makes it hard to deal with compounds whose toxicity is primarily due to surface effects. Managing nanowaste is hard in both developing and developed countries. The rules aren't clear, and people don't always follow them [30]. There is a lot of danger for the individuals who work in these industries and the people who live near them, both now and in the future. We need to find the best ways to measure nanomaterials in order to build a good regulatory strategy. Find specific types of hazardous waste classification and set up detection and monitoring devices that can accurately find and measure amounts of waste in the stream. For eWaste management solutions to work well, they need to have explicit rules that encompass all of these things. This will make it easier to switch to the ideas of a circular economy.

POLYMER COMPOSITES AND NANOCOMPOSITES in E-WASTE TO ENERGY CONVERSION TECHNOLOGIES

Polymer composites and nanocomposites are cutting-edge technologies that can turn electronic trash into sustainable energy. They use advanced materials engineering methods that solve both environmental problems and energy needs. Using novel materials systems in an efficient way combines the benefits of polymer matrixes and nanofillers with functional features that let old electronic parts become high-performance energy conversion devices. Triboelectric nanogenerators (TENG) are one of the best techniques to change mechanical energy into electrical energy. They employ plastic film waste from electronics as the layers that touch each other. This is also a fantastic way to get rid of old electronics [31]. Researchers collected unprocessed plastic trash from customers, including HDPE, PP, and PET, and discovered that batteries could generate over 300V with current densities of 150 $\mu A/cm^2$ when the optimal triboelectric pair matching is applied. Adding conductive nanofillers like MXene nanosheets or carbon nanotubes makes the system perform considerably better. They raise the dielectric constant from 2.65 to 5.74 and keep the charge for more than 10 seconds.

When polymer nanocomposites are mixed with bismuth telluride module components, they transform waste heat from the electrical processing of insulating substrates into power. At a temperature difference of 190°C, the most you can get from thermoelectric energy harvesting is 40 W. Adding change-form ingredients to the polymer matrix makes all of this possible. We may now use thermal energy storage and metering in polymer matrix media to make conversion more efficient in many different situations. Piezoelectric polymer nanocomposites have a lot of potential for turning mechanical vibrations from processing e-waste back into electrical energy. When some nanofillers, such those manufactured from zirconia and created with researchers at Brunel University London, are put into polymer matrixes, they can make piezoelectricity more sensitive by two orders of magnitude. Polymer nanocomposites are also superior at conducting electricity thanks to new manufacturing technologies. For instance, we can now construct nanostructured composite ropes from milled waste polystyrene and PVC by adding functional nanomaterials like NiZn ferrite nanoparticles to make them superparamagnetic and better at transporting heat.

Using either solvent extraction or pyrolysis and electrolysis treatment, sustainable manufacturing processes turn e-waste plastic parts directly into energy-harvesting devices that add value. You can obtain back up to 81% pure polycarbonate from electronic waste and generate hydrocarbon oils with a calorific value of up to 38.27 MJ/g. People also make activated carbon compounds to use in supercapacitors. Their specific capacitances are 220F/g. Integrated systems may make power densities of up to 460mW/m^2 and stay stable for more than 10,000 cycles. This demonstrates the possibility of e-energy engineering with organic polymer nanocomposite technology.

E-waste power technologies use cutting-edge thermal, biochemical, and other processing to turn electronic rubbish into energy in a whole new way. Even while it sought to develop guidelines for controlling e-waste pollution that were in line with international norms, there are still a lot of challenges. The major types of technologies in this group include thermoelectric conversion processes like incineration, pyrolysis, and gasification. These methods use very high temperatures to change sophisticated electronic waste parts into sources of energy that can be used. When e-waste is burned, it burns all the way through at temperatures above 850 °C, with just pretreated air to assist it burn. This method makes steam that powers turbines to make electricity and cuts down on waste by 95–96%. This method is fantastic for getting energy back, but it also causes a lot of difficulties for the environment that need to be fixed. Pyrolysis, on the other hand, has its own set of issues. When it doesn't rain, the process stops. Pyrolysis works best when there isn't a lot of oxygen and the temperature is between 400 and 900 °C. It turns the organic portions of e-waste into solid char, synthetic gas (syngas), and pyrolysis oil. The process changes 90% of the weight into gas, which is 40–45% hydrogen and 20–25% carbon monoxide. You can use this gas to manufacture chemicals or power. Pyrolysis keeps all nonferrous metals safe. The solid stages of this procedure already have most of the important and valuable metals in them. The gas that comes out of it has a calorific value of 15 to 30 MJ/m, depending on what kind of feedstock is used.

The most advanced approach to turn e-waste into a clean-burning gas-syngas is using gasification technology. It does this by using limited partial oxidation at temperatures between 700 and 1400 degrees Celsius. This, in turn, cuts down on dangerous emissions. We are particularly focused on steam gasification in this context. When compared to ordinary pyrolysis, superheated steam is a gasifying agent that cuts the amount of tar by at least 72%. This makes the gas cleaner and better for using as fuel. Plasma torches are used in advanced plasma arc gasification, which breaks down trash into its basic pieces at temperatures of 7000 oC or more. This creates syngas that is incredibly pure and has very little effect on the environment. This process is superior than regular incineration since it makes more electricity (approximately 0–50% more) and puts less harmful chemicals into the air. Because they are adaptable, gasification systems can be employed with combined-cycle power generation. Using clean syngas to power both gas and steam turbines can lead to electrical efficiency of over 40%. Biochemical processes for converting organic materials from e-waste into other substances It provides an alternate approach for converting the organic component of Scavengers through anaerobic digestion or fermentation. Digestion that doesn't need oxygen This procedure uses a variety of bacteria that naturally arise to break down organic materials in an area with minimal air. This creates a form of biogas that is 60% methane and 40% carbon dioxide. Jack Nicholson's mother says to him in Five Easy Pieces, "Therefore, in an anaerobic reactor with no air, this is the same chemical process that occurred in the movie.

The whole process includes three essential parts: breaking down complex organic materials into simpler molecules, making acid by bacteria that make acid, and making methane by Archaea that make methane. These processes can keep things for 20 to 40 days, depending on the situation. You can burn biogas directly to create heat power, or you can change it into biomethane (methane that is just as good as natural gas) and contribute it to natural gas distribution grids. This requires modern biotechnology systems that use nanocatalysts and genetically modified microorganisms that work better in human-made indoor spaces. The best technique to handle mixed e-waste streams is to use hybrid systems that combine biochemical and thermal processes. The greatest approach to recover energy back is to get rid of things like dioxin, furans, and PCBs. In short, These technologies can transform electronic waste from something that hurts the environment into something that creates a lot of energy. This goes along with the idea of a circular economy since it promotes values while also addressing significant challenges of sustainability in renewable energy production and waste management.

NANOPARTICLE RECOVERY AND RESOURCE VALORIZATION USING POLYMER

Polymer-assisted nanoparticle recovery, on the other hand, uses innovative polymeric systems to retrieve useful nanoparticles out of diverse types of waste streams, keep them stable, and return them. There are several ways this can happen. Using emulsification, nanoprecipitation, or phase inversion techniques, you can make polymeric nanoparticles that let you manage their size, how well they encapsulate things, and their surface qualities. The sizes of these things are between 10 and 200 nanometers. Polymer inclusion membranes (PIMs) built with nanoparticles like ferrite (FeO4 3) can get rid of 80% of both arsenate and phosphate ions in water samples that are dirty. This method, on the other hand, only works on some types of trash and in some regions to clean up land that has been polluted.

Advanced polymer-coated nanoparticles make it easier to get valuable metals out of electronic waste by regulating the chemistry of the surface and selective binding. Naddiction. Microfluidic technology has been created to generate polymeric nanoparticles that are of the same size. These nanoparticles are important for making recovery procedures bigger. To function successfully for both size distributions and large-scale up operations, engineering control needs an even more comprehensive collection of options that work together. By combining sustainable polymers like lignin, cellulose triacetate, and biodegradable polyesters, waste resources can be transformed into high-value nanocomposites. We can do this to close loops of resources without changing the environment. This would also help protect traditional sectors that depend on raw materials that are running out soon.

Using these systems, performance-confident through optimized zeta potential values (±30 mV), controlled surface functionalization, and target species selective recovery promotes recycling and saves resources; those are two main concepts in every circumstance. It could get the most out of outdated electronics by using new production technologies to recover and revalue nanoparticles found in electrical waste. We also want to take a more thorough approach to fixing some of the big problems we have with materials management and putting a circular economy into action. The procedure begins with improved extraction and separation techniques that can pull nanoparticles out of the complex matrices of e-waste. This is possible because nanoparticles have unique physicochemical features. There is a lot of promise in advanced laser ablation techniques. For instance, using picosecond UV lasers to get gold nanoparticles directly from printed circuit boards with 90% purity and an average particle size of 100 nm not only gets rid of the need for harsh chemical solvents, but it also lets you watch the recovery process in real time using Laser-Induced Breakdown Spectroscopy. There are also alternative ways to achieve this that aren't bad for the environment, such selective leaching with other chemicals. Ammonia, citric acid, and ascorbic acid are three examples of chemicals that may effectively extract metal nanoparticles such as copper oxide, silver, or gold, maintaining regulated size distributions ranging from 1 to 30 nanometers. All of these procedures will be safe for the environment and for people's health if bioleaching technologies that use microorganisms like Acidithiobacillus ferrooxidans are applied. They let you selectively take out ultrafine nanoscale copper nanoclusters that are only 1 nanometer in size, and they don't cause much pollution.

These are critical actions to take when dealing with nanoparticle disposal problems, and they require to use modern separation technology to work. An adjuster with a lot of reduced metal can use chemical precipitation to get rid of full waste gas tanks. This means that you can get back more than 95% of valuable metals like gold, silver, and platinum. Nanoparticles are created in a fully controlled electrowinning process. The items are vaccine crystals that are created only for advanced usage and are very pure. Column seismology chromatography, gravity desorption, and tangential flow filtering are the best ways to clean things up. You can separate nanoparticles of various sizes by utilizing membrane filters with varied characteristics in a staged ultrafiltration process. You may, for example, split colloidal gold and silver particles that are between 3 and 50 nanometers broad into groups with extremely specific width gradients, from roughly 1m,000 within each subgroup to 300,000 per second. Density gradient centrifugation helps you distinguish shapes, which is a vague term for shape, by how closely particles are packed together in membranes. At this stage, this approach can split nanoparticles that are structured like spheres into a "conical" assembly. From this point on, no other types of nanoparticles will be able to join.

RESULTS AND DISCUSSIONS

The worth of resources being realized Making nanoparticles that are very valuable is also part of business. These items have new features and are also helpful for business. There are several ways to use recovered nanoparticles, including in electronics, biomedicines, environmental cleanup goods, energy storage systems, and catalysis. The market price of these goods is substantially more than the price of the raw ingredients. Gold nanoparticles taken from e-waste are very good in catalyzing organic conversion processes. For example, they can reduce nitropyridine to k1 values of up to 1.1×10^{-3} s^{-1} and stay stable and reusable for many cycles. Silver nanoparticles produced from electronic trash are far better at killing bacteria and breaking down contaminants. This makes them ideal for cleaning water and for covering things like biomedical applications and copper foils. The economy's possible growth First, nanoparticle valorization has a lot of potential for making money: Those materials that are hard to get rid of are worth billions of dollars. The things that are thrown out every year may continue earning money for replacements forever. Another thing is that advanced hydrogel-based extraction techniques are quite good at getting pure gold nanopowder.

The definition of "national purity" comes out to be 23.78k, even in complicated liquid media that is full of copper and nickel ions. The integration of green synthesis methods that use natural reducing agents and biocompatible matrices is another key technology. This makes isolated nanoparticles even better for the environment because they stay functional and high-quality. Advanced separation technologies, quality control measures, market development plans that recognize inherent value, and suitable regulatory procedures must all work together to get nanoparticles back and employ them.

CONCLUSION

Managing electronic trash, nanoparticles, cutting down on CO2, and developing resources is a new step toward sustainable materials stewardship and procedural integration principles in a banned setting. Using modern thermal conversion, biological digestion, and hybrid technologies to their utmost may turn even the smallest electronic waste products into useful energy resources with little influence on the environment. Pyrolysis, gasification, and plasma treatment technologies turn the parts of complicated electronic devices into clean synthetic gases and liquid biofuels without any waste. They are also quite good at what they do. Biochemical technologies like nanocatalysis can speed up anaerobic fermentation and make them into decentralized, low-emission paths for biogas. This adds even more renewable energy sources.

The most important parts of this transformation is how nanoparticles, such as gold, silver, copper, and rare earth metals, are now recycled and reused. Some of them are selective leaching, laser ablation, bioleaching, and membrane procedures of purification. These procedures can get you very pure nanoparticles back with a high recovery rate. These high-quality products can be employed in medical science, electronics, environmental restoration, and catalysis. Using recycled nanoparticles not only saves money on reprocessing trash, but it also cuts down on pollution caused by mineral extraction, gets rid of supply risks caused by geopolitics, and cuts down on the need for primary mining.

Companies need to get beyond a lot of technological, economic, and regulatory difficulties before they can fully take advantage of nanoelectronics waste management. To handle high operating expenses, make sure staff have long-lasting security systems, and cover in the gaps in nanomaterials regulation, we will require coordinated policies, industry standards, and cooperation between the public and private sectors. Environmental risk analysis and life cycle evaluations are particularly crucial for making the conversion and recovery process safe, clean, and truly sustainable. Systems that can grow and are cheap This is achievable because experts from diverse industries work together to get rid of dangerous waste and obtain valuable metals back. These solutions will also help clean up the environment and make the globe safer for energy. Because electronics recycling is now a global business, 100% of items can be recycled and reprocessed. This implies that materials are always used again. We need new rules, global standards, and public-private partnerships that only work when they are needed to get past these difficulties.

REFERENCES

1. Acharya, S. and Sahu, J.N., 2023. Nanomaterials in Waste Streams: Recovery and Valorization. Oxford: Elsevier.
2. Bhattacharya, A., Misra, S.K. and Kumar, P., 2024. “Pyrolysis of Electronic Waste for Syngas Production,” Journal of Cleaner Production, 363, p.132589.
3. Chatterjee, S., 2022. Circular Economy Approaches in E-Waste Management. New Delhi: TERI Press.
4. Das, R. and Roy, S., 2025. “Plasma Gasification of Nanoparticle-Rich E-Waste,” Waste Management, 148, pp.145-156.
5. de Oliveira, L.F.L., 2021. Waste-Derived Nanoparticles: Synthesis Approaches, Characterization, and Applications. Cham: Springer.
6. Dubey, N.K., 2024. E-Waste to Energy Conversion: Principles and Practices. London: CRC Press.
7. El-Zein, A., 2023. “Gasification of Printed Circuit Boards for Hydrogen-Rich Gas,” International Journal of Hydrogen Energy, 48(12), pp.5432-5444.
8. European Commission, 2022. Circular Economy Action Plan. Brussels: Publications Office of the European Union.
9. Fan, Y. and Li, H., 2024. “Bioleaching of Precious Metal Nanoparticles from E-Waste,” Journal of Hazardous Materials, 442, p.130960.
10. Gao, Y., Liu, J. and Tang, Z., 2025. “Selective Recovery of Nanoscale Copper Particles from Printed Circuit Boards,” ACS Sustainable Chemistry & Engineering, 13(4), pp.2105-2114.
11. International Renewable Energy Agency (IRENA), 2023. Waste to Energy: Technology Brief. Abu Dhabi: IRENA.
12. Kang, S.H. and Lee, J.Y., 2024. Nanocatalysts for Enhanced Waste-to-Energy Conversion. Cham: Springer.
13. Kumar, A., 2022. Environmental and Health Risks of Nanoparticles in Waste Streams. Heidelberg: Springer Nature.
14. Li, X., Zhang, T. and Wang, Q., 2023. “Life Cycle Assessment of E-Waste Gasification,” Renewable and Sustainable Energy Reviews, 158, p.112055.
15. Liu, P., 2025. Advanced Thermal Treatment of Electronic Waste. New York: Wiley.
16. Mehta, R.K. and Singh, V., 2023. “Nanoparticle-Enabled Anaerobic Digestion of Organic E-Waste Fractions,” Bioresource Technology, 376, p.132292.
17. Ministry of Environment, Forest and Climate Change (MoEFCC), 2022. Guidelines for Environmentally Sound Management of E-Waste. New Delhi: Government of India.
18. Montoya, I., 2024. Nanoparticle Recovery Technologies: From Lab to Industry. London: Woodhead Publishing.
19. Müller, R., 2023. Sustainable Engineering for E-Waste Valorization. Berlin: De Gruyter.
20. OECD, 2021. Nanomaterials in Waste Streams: Policy Implications. Paris: OECD Publishing.
21. Patel, M., 2025. Waste-to-Energy Conversion Systems: Design and Optimization. Boca Raton: CRC Press.
22. Qiao, B., 2024. “Membrane-Based Separation of Electronic Waste Nanoparticles,” Separation and Purification Technology, 285, p.120387.
23. Sharma, S. and Gupta, M., 2023. E-Waste Management and Circular Economy. New Delhi: Cambridge University Press India.

24. Singh, A. and Kumar, R., 2024. "Environmental Impact of Nanoparticle-Rich E-Waste Landfill Leachate," Environmental Pollution, 316, p.120751.
25. Smith, J. and Brown, L., 2022. Fundamentals of Nanotechnology in Waste Management. Amsterdam: Elsevier.
26. United Nations Environment Programme (UNEP), 2023. Global E-Waste Monitor 2023. Nairobi: UNEP.
27. Zhang, Y., Chen, X. and Sun, W., 2025. "Valorization of Precious Metal Nanoparticles from Waste Printed Circuit Boards," Journal of Materials Chemistry A, 13(8), pp.3698-3709.
28. Aruchamy K, Karuppusamy M, Krishnakumar S, Palanisamy S, Jayamani M, Sureshkumar K, Ali SK, Al-Farraj SA. Enhancement of Mechanical Properties of Hybrid Polymer Composites Using Palmyra Palm and Coconut Sheath Fibers: The Role of Tamarind Shell Powder. BioResources. 2025;20(1): 698–724. Doi: 10.15376/biores.20.1.698-724
29. Palanisamy S, Kalimuthu M, Santulli C, Palaniappan M, Nagarajan R, Fragassa C. Tailoring epoxy composites with Acacia caesia bark fibers: Evaluating the effects of fiber amount and length on material characteristics. Fibers. 2023 Jul 17;11(7):63.
30. Karuppiah G, Kuttalam KC, Palaniappan M, Santulli C, Palanisamy S. Multiobjective optimization of fabrication parameters of jute fiber/polyester composites with egg shell powder and nanoclay filler. Molecules. 2020 Nov 27;25(23):5579.
31. Santulli C, Palanisamy S, Kalimuthu M. Pineapple fibers, their composites and applications. In: *Plant Fibers, their Composites, and Applications*. Woodhead Publishing: Cambridge; 2022. p. 323-346.