STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Issue 1, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/JOPC/

Research JoPC

Development of Biomass-Derived Composites From Commodity Plastics Via Pyrolysis For Enhanced Corrosion Protection of Metals

Lalita[1] , Rajnish Kumar[2], Prasadaraju Kantheti[3], Anahas Perianaika Matharasi Antonytraj[4]
Arvind Lal[5], Ashwani Kumar Sanghi[6,]*

Abstract

Escalating environmental concerns and the depletion of fossil resources have spurred the need for sustainable and eco-friendly materials. By converting plastic waste into valuable carbonaceous materials via pyrolysis, both plastic pollution and resource scarcity can be addressed. The process involves the thermal decomposition of plastics in an inert atmosphere, producing a mixture of gases, liquids, and solid residues rich in carbon. These carbonaceous residues are then incorporated with biomass materials to create hybrid composites. The resulting composites exhibit superior physicochemical properties, including enhanced mechanical strength and thermal stability. Comprehensive analysis demonstrates that these biomass-derived composites significantly improve the corrosion resistance of metal substrates. Electrochemical testing shows a marked reduction in corrosion rates, attributed to the effective barrier properties and the active inhibition mechanism of the composites. Furthermore, surface characterization techniques such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) reveal a uniform and adherent protective layer on the metal surfaces. The development of these innovative composites presents a promising avenue for the sustainable management of plastic waste while providing an effective solution for metal corrosion protection.

***Author for Correspondence**
Ashwani Kumar Sanghi
E-mail: dr.ashwanikumarsanghi@mvn.edu.in

[1]Ph.D. Scholar, School of Allied Health Sciences, MVN University, Delhi-Agra Highway, Palwal, Haryana, India
[2]Assistant Professor, School of Allied Health Sciences, MVN University, Delhi-Agra Highway, Palwal, Haryana, India
[3]Assistant Professor, Department of Mechanical Engineering,Sagi Ramakrishnamraju Engineering College AP, Bhimavaram, india
[4] Assistant Professor, Department of Research Analytics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai , Tamil Nadu, India.
[5]Assistant Professor, Department of Chemistry, Central University of Jharkhand, Ranchi, Jharkhand, India
[6]Professor, School of Allied Health Sciences,MVN University, Delhi-Agra Highway, Palwal, Haryana, India

Received Date: July 20, 2024
Accepted Date: August 13, 2024
Published Date: October 09, 2024

Citation: Lalita, Rajnish Kumar, Prasadaraju Kantheti, AnahasPerianaikaMatharasi Antonytraj, Arvind Lal, Ashwani Kumar Sanghi. Development of Biomass-Derived Composites from Commodity Plastics via Pyrolysis for Enhanced Corrosion Protection of Metals. Journal of Polymer & Composites. 2025; 13(1): 59–70p.

Keywords: Biomass-derived composites, commodity plastics, pyrolysis, thermal decomposition, metal corrosion protection.

INTRODUCTION

Over 330 million tonnes of plastics are manufactured annually worldwide, with 60 million tonnes generated in Asia. Their commercial, industrial, and residential service lives vary from less than a year to more than 50 years due to the diverse uses and types of plastics [1]. Inevitably, a significant portion of plastic ends up in the waste stream. In Asia, waste plastics are produced at a rate of about 27 million tonnes annually. Approximately 42% of plastic waste is managed through energy conversion (mostly through garbage incineration), 27% is disposed of in landfills, and 31% is recycled [2].

Thermochemical recycling, primarily achieved through gasification and pyrolysis, aims to produce fuel oils, gasoline, syngas, and other higher-value products [3-4]. Pyrolysis, a common feedstock regeneration method, involves heating plastic to moderate temperatures (around 500 °C) in the absence of oxygen, resulting in lighter molecules that can be condensed into oil or gas products. Several studies have reviewed pyrolysis as a plastic waste management technique [5].

Thermal degradation, which converts plastic waste into useful items like fuels due to their hydrocarbon content. Pyrolysis transforms contaminated and mixed polymers into streams of liquid, gas, and solid products using thermal energy without oxygen [6]. Waste plastics have a high calorific value, resemble petrochemical fuel in structure, and originate from fossil fuel sources, making them a viable energy source. The pyrolysis process can be adjusted to optimize the production of desired outputs, making it a flexible method. Pyrolysis methods yield significantly more olefin products than gasification [7].

Re-polymerizing these unsaturated hydrocarbons can close the loop on a fully sustainable economy by creating new plastics from recycled materials. Numerous studies have explored different aspects of plastic waste recycling through decomposition [8]. Documented the impact of various polymers and other factors on the yield and quality of pyrolytic oil, and its physical and chemical properties. Focused on the technology of Municipal Solid Waste (MSW) pyrolysis, its products, and ways to mitigate its environmental impact [9]. Examined the composition of pyrolytic oil and the effects of temperature and storage time on the pyrolysis process in catalytic pyrolysis research covered the techno-economic assessment and kinetic studies of the process [10].

These studies provide an overview of recent methods for pyrolyzing waste plastic, particularly for producing pyrolytic oil. There is limited discussion in the public literature about contaminants and the need to improve pyrolysis products. A relevant, current review the implications for steam cracking and the contaminant content of consumer-derived pyrolysis oil. The investigation revealed that contamination levels were at least two orders of magnitude higher than acceptable limits, highlighting the need for intermediary upgrading processes to convert recycled plastic into useful chemicals [11].

Related Works

Pyrolysis is conducted without air, in contrast to gasification or the combustion process, which both require excess oxidizing agents or occur under stoichiometric conditions. During pyrolysis, macromolecular polymers break down into smaller molecules, including various hydrocarbons and oxygenates from oxygen-containing plastics like PET [12]. As shown in Table 1, the temperature range and residence time determine the type of decomposition and the resulting products [13].

Table 1. Pyrolysis Procedures Customized For The Intended Products And Operational Circumstances.

Pyrolysis type	Operating temperature	Heating rate	Residence time	Atmosphere	Main products
Slow Pyrolysis	300-700°C	Low (0.1-1°C/s)	Long (hours to days)	Inert (N2, Ar)	Biochar, tar, syngas
Fast Pyrolysis	400-600°C	High (10-200°C/s)	Short seconds)	Inert (N2, Ar)	Bio-oil, syngas, char
Flash Pyrolysis	450-1000°C	Very High(>1000°C/s)	Very Short (milliseconds)	Inert (N2, Ar)	Bio-oil, syngas
Catalytic Pyrolysis	300-700°C	Variable	Variable	Inert (N2, Ar)	Bio-oil, upgraded hydrocarbons, syngas
Microwave Pyrolysis	200-600°C	Variable	Variable	Inert (N2, Ar)	Bio-oil, syngas, char
Hydro-Pyrolysis	300-500°C	Moderate	Variable	Hydrogen-rich	Bio-oil, syngas, water-soluble organics

For natural fiber-reinforced resin matrix composites to be widely employed as engineering materials, they must overcome several obstacles [14]. A significant disadvantage is the considerable variation in these composites' mechanical properties, often linked to lower mean values for those properties [15-16].

The polymer composition of polystyrene is aromatic, and when the polymer is thermally cracked, it yields an aromatic product slate containing substantial amounts of styrene (approximately 50–79 weight percent) and additional aromatic elements such as xylene, toluene [17]. As chlorine is gradually eliminated from the polyvinyl chloride framework, aromatic chemicals are produced through the formation of C=C bonds and cyclization. Processing additives like FeOOH or Fe3O4 can adsorb the HCl. The linear, aromatic, and oxygenated hydrocarbon compounds in polyethylene terephthalate break down by heat [18].

Polystyrene decomposes via two primary mechanisms: unzipping and random scission. Styrene is the most commonly produced derivative, with trace amounts of its dimer and trimer also present. Aromatic compounds such as toluene and benzene are produced from the unstructured chain. To make the byproducts of pyrolysis suitable for chemical treatment, they need to be further upgraded due to their separation.

Research Gap

Limited understanding of the long-term stability of biomass-derived composites in harsh environments.

Inconsistent quality and properties of pyrolysis products from different plastic waste sources.

Lack of scalable and cost-effective pyrolysis processes for industrial applications.

Insufficient data on the environmental impact of the entire life cycle of biomass-derived composites.

Need for optimization of composite formulations to maximize corrosion protection efficiency.

Limited integration of advanced characterization techniques for in-depth analysis of composites.

Inadequate exploration of synergistic effects between different biomass materials and carbonaceous residues.

Gaps in regulatory standards and guidelines for the use of biomass-derived composites in industry.

PROPOSED SYSTEM

The development of composites derived from biomass using pyrolysis to enhance metal protection against corrosion offers an intriguing intersection of multidisciplinary research addressing industrial and environmental concerns. This study focuses on utilizing pyrolysis—a process involving the thermal decomposition of polymers in an inert atmosphere—to convert recyclable plastics into valuable carbon-rich materials shown in Figure 1. These carbonaceous residues are blended with other biomass components to create hybrid composites. These composites exhibit superior durability and thermal stability, making them highly effective for corrosion prevention on metal surfaces.

The findings underscore the potential of these innovative materials to provide robust barrier properties and active inhibitory mechanisms, thereby enhancing corrosion resistance significantly. This research represents a valuable synergy between waste valorization and material science, offering an eco-friendly approach to managing recyclable plastics and advancing the development of high-performance materials for industrial applications.

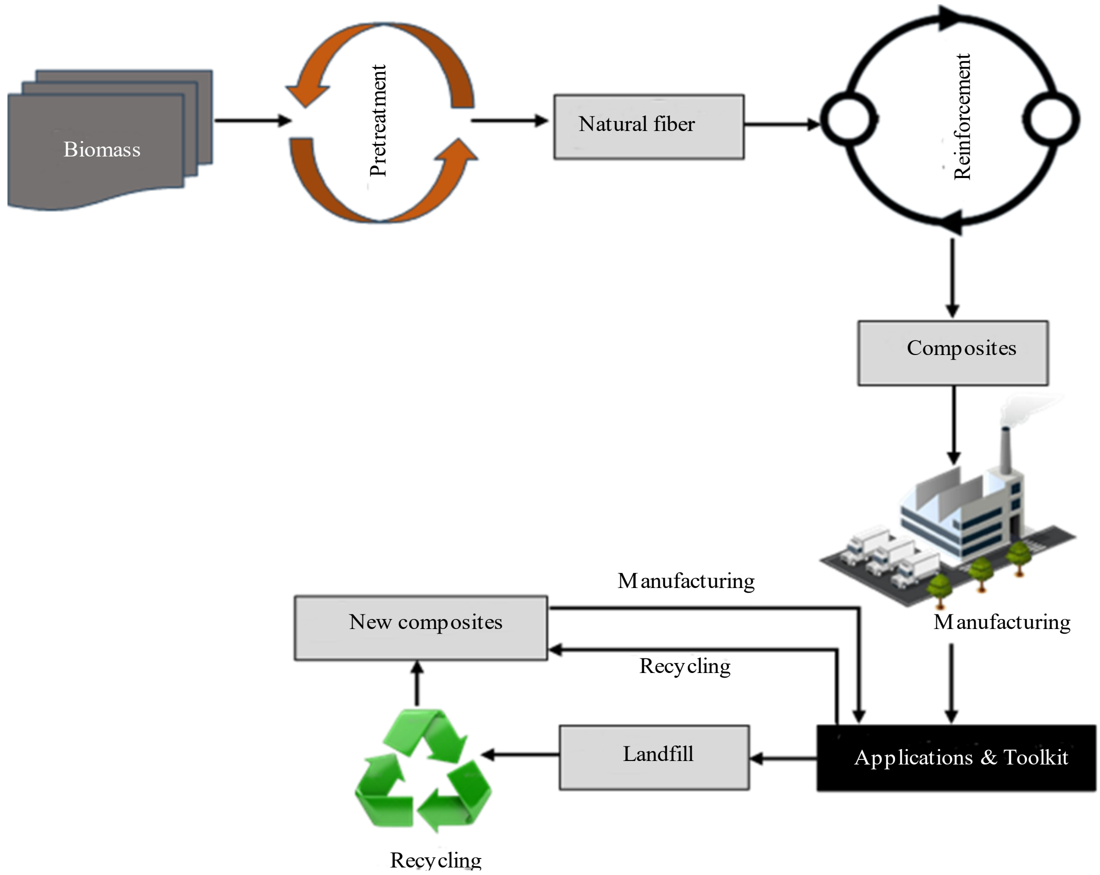

Figure 1. Proposed architecture.

Developments in Pyrolysis Product and Waste Plastic Analysis

The waste stream of plastic contains various contaminants such as paper, food scraps, metals, and numerous other materials, all composed of different polymers. Characterizing the waste stream is crucial for effective waste management. Identifying contaminants is particularly important in determining the recycling pathway for waste plastics. Techniques like ultra-trace metal analysis (ppb level) using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) are employed for this purpose. Combustion Ion Chromatography (CIC) is utilized to quantify sulphur and halogens. This method involves pyrolyzing the sample in an oxidizing environment, collecting the resulting vapours on a suitable adsorbent, and then analysing them using ion chromatography.

Furthermore, elemental analysis using an elemental analyser is used to determine the composition of waste plastics in terms of carbon (C), hydrogen (H), nitrogen (N), sulphur (S), and oxygen (O). Thermo Gravimetric Analysis (TGA) is employed to assess the thermal conductivity of plastic waste. Recyclable plastics are also subjected to Fourier-Transform Infrared Spectroscopy (FTIR) analysis to identify organic, polymeric, and inorganic components and their functional groups. These analytical techniques collectively aid in understanding the composition and characteristics of waste plastics, guiding effective recycling strategies and waste management practices.

The pyrolysis process involves the thermal decomposition of commodity plastics (e.g., polyethylene, polypropylene) to produce carbonaceous residues. This can be represented by the general reaction:

Plastic → Carbonaceous Residue + Gases/Liquids

The kinetics of pyrolysis can be described by Arrhenius equation:

$$r = Aexp(-\frac{E}{RT}) \quad (1)$$

Where:r -reaction rate,A - pre-exponential factor,E - activation energy,R - universal gas constant,T - temperature.

Plastic Separation Using Biomass

Pyrolysis of plastics such as Polyvinyl chloride (PVC) and Polyethylene terephthalate (PET) which are common in municipal plastic waste (MPW), can generate hazardous materials shown in Figure. 2. Processes like oxidation or combustion of these hydrocarbons, especially those containing chlorine, can lead to the formation of other hazardous compounds like dioxins and furans. The thermal breakdown of PET produces carbonic acids such as benzoic and terephthalic acids, which can pose challenges for pyrolysis plants due to their tendency to cause corrosion and pipe clogging at ambient temperatures. Recycling PET through mechanical or chemical methods, such as hydrolysis, methanolysis, glycolysis, and aminolysis, is often more favorable compared to PET pyrolysis. These processes can fully depolymerize PET, providing a pathway to recover valuable components.

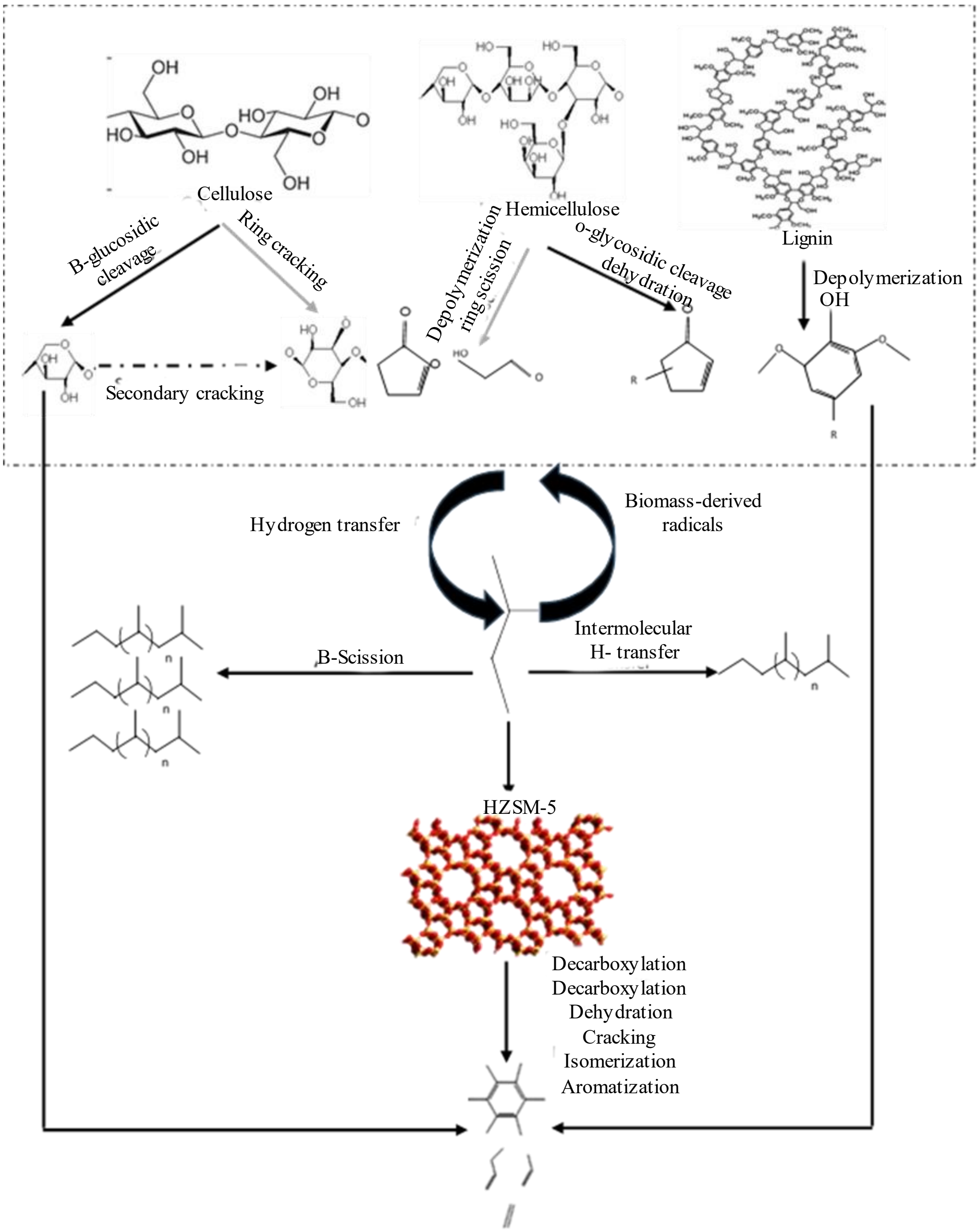

Figure 2. Procedure of separating plastic using biomass.

Incorporation of Biomass Materials: The carbonaceous residues obtained from pyrolysis are then blended with biomass materials (e.g., wood chips, sawdust) to form composite materials. The blending process and the resulting composition can be expressed as:

$$Composite = f(PlasticResidue, BiomassMaterial) \quad (2)$$

Here, f denotes the mixing or blending function.

Characterization and Property Enhancement

Mechanical strength: The mechanical properties of the composite can be evaluated using equations such as Young's modulus or tensile strength tests.

Thermal stability: Thermal stability can be assessed through techniques like thermogravimetric analysis (TGA), where the degradation behavior can be described by:

$$\frac{dW}{dt} = -kW^n \quad (3)$$

Corrosion protection: The corrosion protection efficacy can be quantified using electrochemical techniques, such as Tafel extrapolation to determine corrosion rates:

$$CorrosionRate = \frac{B}{x_{corr}} \quad (4)$$

Where B is a constant and x_{corr} is the corrosion current density.

Pyrolysis for Enhanced Corrosion Protection of Metals

Pyrolysis for Enhanced Corrosion Protection of Metals: The process of pyrolysis is the heat breakdown of organic materials—like plastics—without the presence of oxygen. This technique may provide carbonaceous substances with large surface areas, chemical inertness, and excellent barrier qualities—all of which are advantageous for preventing corrosion shown in Figure.3.

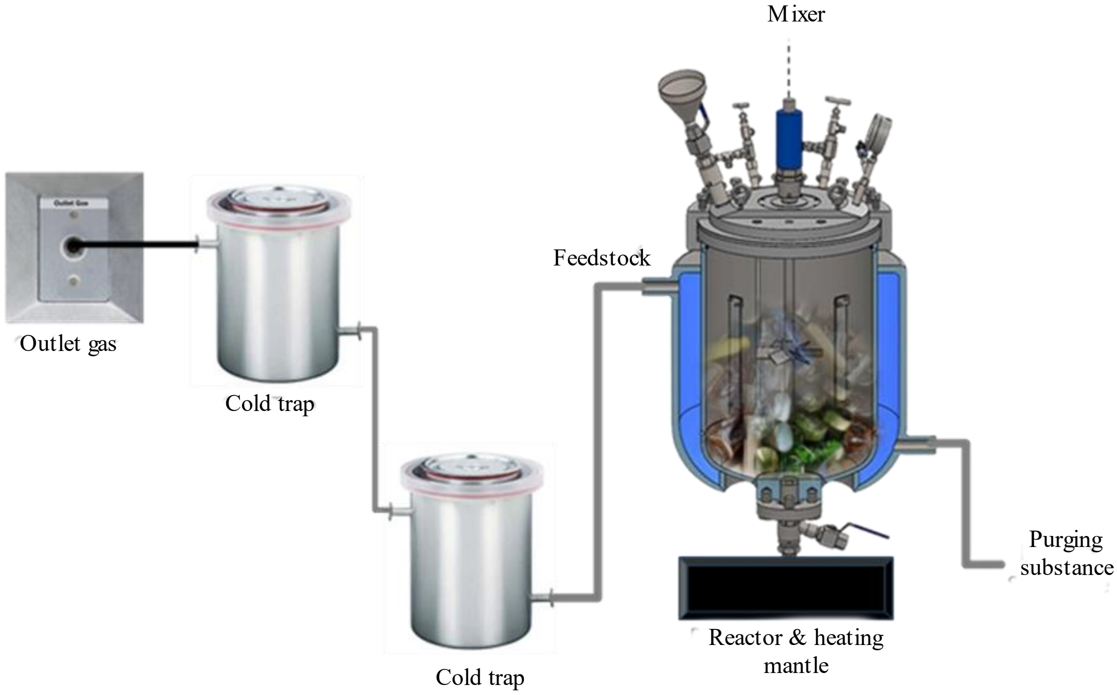

Figure 3. Procedure of pyrolysis for enhanced corrosion protection of metals.

Carbonaceous Residue Formation

- Carbon-based residues are among the byproducts of pyrolysis; these residues may be identified by their physical makeup and characteristics that are important for preventing corrosion, such as their dimension and chemical composition.
- *Corrosion prevention processes*: Pyrolysis-derived carbonaceous compounds can provide corrosion protection in several ways, including:
- *Barrier protection*: By acting as a material barrier, the carbonaceous layer lessens the metal substrate's exposure to corrosive conditions.
- *Inhibition*: By adhering to the metal appearance, chemical species present in carbonaceous substances can prevent processes of corrosion.

Corrosion Rate Reduction

The corrosion rate reduction can be quantified using electrochemical techniques, such as Tafel extrapolation. The corrosion current density (corr) obtained from Tafel analysis relates to the corrosion rate CR through the equation:

$$CR = \frac{x_{corr} - 3.27.10^5}{\rho . A} \quad (5)$$

Where: CR is the corrosion rate in mm/year, x_{corr} is the corrosion current density in A/cm², ρ the density of the metal in g/cm³, A is the atomic weight of the metal

By creating carbonaceous compounds, pyrolysis is a potentially effective way to improve the corrosion resistance of metal. Optimizing materials for practical use in businesses that demand long-lasting and sustainable corrosion-resistant systems is made possible by a fundamental knowledge of reaction kinetics, product character development, and processes associated with corrosion

HDPE was pyrolyzed using both heat & catalytic methods at three distinct temperatures (400, 450, and 500 ◦C). HZSM-5 catalyst with 1% (w/w) loading was employed shown in Figure. 4. Both thermal especially catalytic pyrolysis showed higher gas yields when the pyrolysis temperature was raised, and the result concentration fell into the C2-C8 range. With the catalyst, the gas yield at 500°C was about 100%, with a C2-C6 distribution of the gas shown in Figure. 5. Compared to thermal pyrolysis, the total O/P ratio in catalytic pyrolysis was nearly raising the coolant temperatures at the reactor output may also boost the gaseous yield and raise the finished product's mean molecular mass. With the help of this innovative, straightforward design, HDPE may be transformed into useful short olefins for the petrochemical sector.

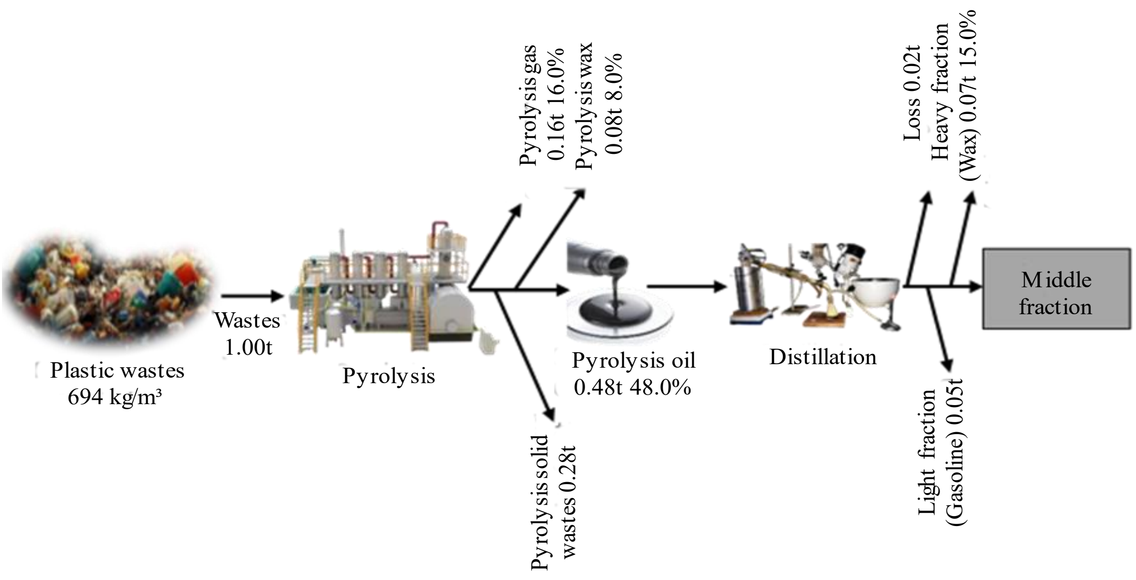

Figure 4. Pyrolysis process plastic waste mass balance

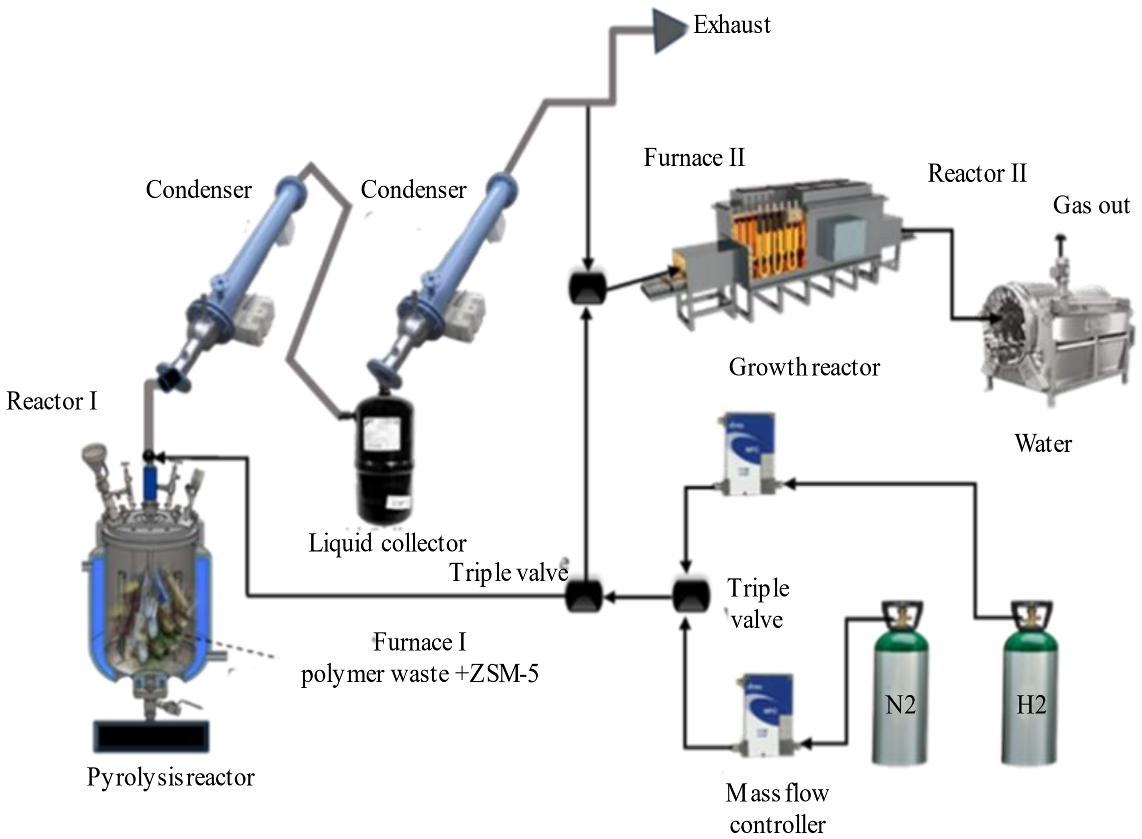

Figure 5. Polyethylene with intermediate condensation of pyrolysis-catalysis

RESULTS AND DISCUSSONS

Under a manufactured pyrolyzing system, biochars from various sources of biomass were pyrolyzed for 30, 40, 50, and 60 minutes of residence. The carbon concentration of these biochars is ascertained via proximate measurement. Furthermore, BET was utilized to analyze the area of surface & pore size to select the optimal biochar source for the creation of conductive HDPE polymer composites for usage in electromagnetic shielding applications. Additionally, the best biochar (pine wood biochar) was examined for its heavy metal concentration and additional FTIR.

Pyrolysis Residence Time

The experimental average pyrolysis temperature measured using data logger for each biomass source with respect to different pyrolysis residence time is depicted in Table 2.

Table 2. Experimental Average Pyrolysis Temperature.

Pyrolysis time	CHB	PWB	SBB	MCB
30 min40 min 50 min 60 min	586.80 603.56 618.08 614.30	590.67 609.43 619.98 621.35	593.66 598.18 604.38 612.60	588.77 607.05 621.54 618.80

Surface examination of biochar using SEM To confirm the porosity levels discovered via BET research, an automated laser microscopy surfaces morphological picture of the pine wood biochar was additionally performed, as seen in Figure. 6.

Pyrolyzed at 30, 40, 50, and sixty minutes respectively usually attain all the necessary desirable characteristics when the pine wood is pyrolyzed at 60 minutes (increased area of the surface, pore radius, volume of pores, and carbon material).

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

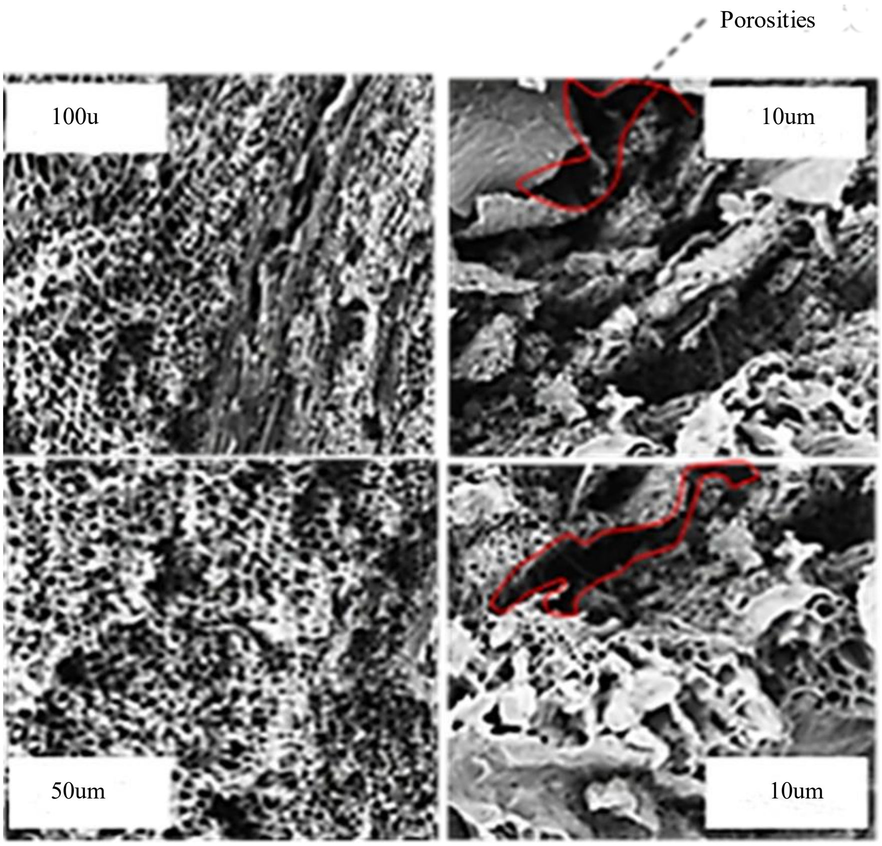

Figure 6. SEM result of pine wood biochar (a) 100µm, (b) 10µm, (c) 50µm and (d) 10µm.

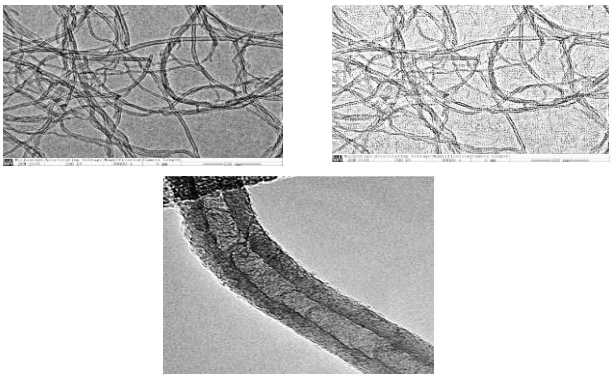

Figure 7. Carbon nanotubes produced waste plastic (a) SEM image; (b) Raman spectroscopy; (c) TEM image.

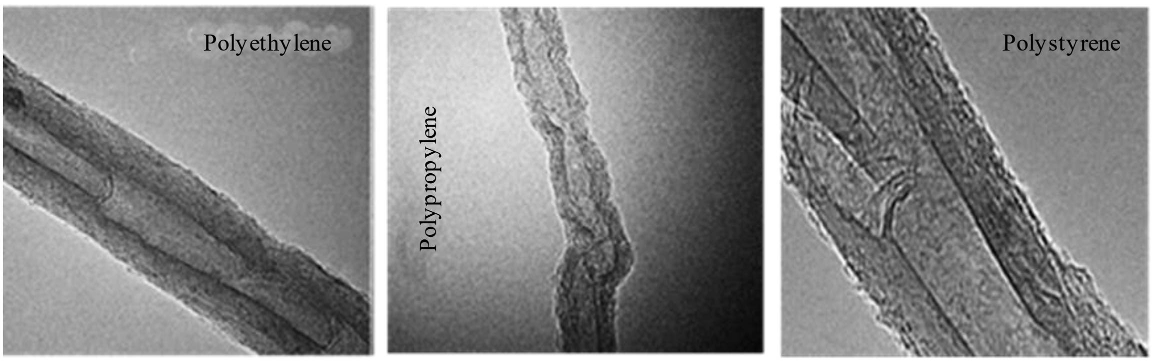

Figure 8. TEM image from different plastic waste

Pinewood that has been biochar pyrolyzed for 60 minutes is therefore chosen as the best filler shown in Figure 7. Pinewood biochar's atomic spectrum study revealed no concentrations of lead, chrome, or cadmium and the three heavy metals.

A common method for assessing the standard of CNTs generated is the G:D ratio, which is the ratio between these two peak levels; a greater value indicates a higher grade or impurity of CNTs in Figure. 8 indicates a lower level of CNT purity. The generated spectrum reveals peaks at 1589 & 1348 cm^{-1}, which correspond to the G peak and the D peak, respectively. The G peak is linked to graphitic carbon networks inside the sample, whereas the D peak is related to deficiencies in the graphic lattice or unstructured carbon molecules. Moreover, the G' peak, which is linked to the two-photon elastic dispersion processes may be utilized for assessing the pureness of carbon nanotubes, which is seen at 2709 cm^{-1}.

The carbon-based deposition made of polyethylene, polypropylene, & polystyrene is depicted in Figure. 9. All of the polymers were confirmed to contain multi-walled nanotubes of carbon, which had morphologies comparable to each other, with diameters of 10–20 nm and lengths of several hundred nm. All the plastics had various yields of carbon nanotubes (CNTs).

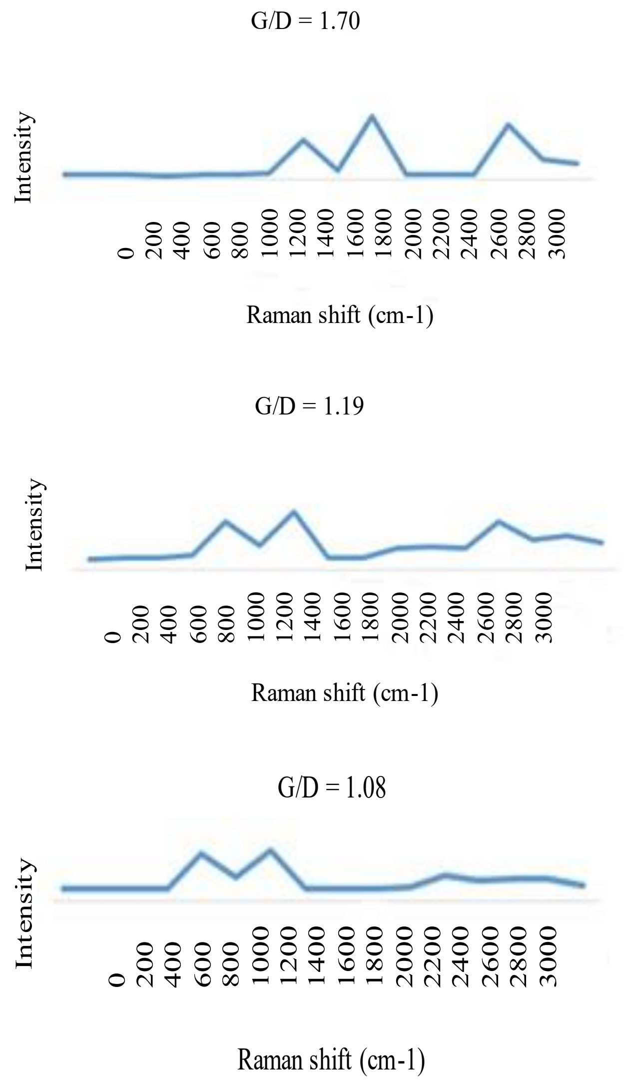

Figure 9. Raman spectrographs from different plastic waste.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Table 3. Surface Roughness on Different Samples.

Sample	Surface roughness (Ra) (micrometres)
1	0.26
2	0.28
3	0.31
4	0.29
5	0.27
6	0.30
7	0.32
8	0.27
9	0.29
10	0.28

Table 4. Vickers hardness on different samples

Sample	Vickers Hardness (HV)
1	222
2	216
3	226
4	219
5	223
6	218
7	224
8	217
9	225
10	220

Table 3 compares the outermost texture of several specimens by displaying the surface roughness values (Ra), expressed in micrometres, for every one of the ten examples. Table 4 presents the Vickers hardness values (HV) of each of the 10 samples, providing a comparison of hardness levels across different specimen

CONCLUSIONS

An important development in materials science and environmental sustainability is the creation of composites made from biomass using commercial polymers and pyrolysis to improve metal corrosion resistance. This study has demonstrated the feasibility of pyrolyzing plastic waste into useful carbonaceous elements, which can then be combined with biomass components to create a novel composite. Compared to conventional coatings or materials, these composites exhibit improved durability, thermal endurance, and, most importantly, superior corrosion resistance. This protective layer significantly reduces corrosion rates by acting as an effective barrier against corrosive substances. By utilizing advancements in pyrolysis technology, this technique not only mitigates environmental impact but also provides an affordable and efficient means of creating corrosion-resistant solutions for various metal substrates.

The creation of biomass-derived composites from commodity plastics through pyrolysis offers a viable way to meet industry demands for long-lasting and sustainable materials while positively influencing global waste management and environmental sustainability efforts. Further research in this field may lead to improved composite formulations and scalable manufacturing processes, expanding the application of these innovative materials across various commercial sectors.

REFERENCES

1. Sahoo, G., Dash, A. C., Roul, P. K., & Handa, A. K. (2024). Fundamentals and potentials of biomass-derived materials for sustainable issues. In *Plant Biomass Applications* (pp. 293-318). Academic Press.J
2. Saeed, M., Shahzad, U., Rabbee, M. F., Manzar, R., Al-Humaidi, J. Y., Siddique, A., ... & Rahman, M. M. (2024). Potential Development of Porous Carbon Composites Generated from the Biomass for Energy Storage Applications. *Chemistry–An Asian Journal*, e202400394.
3. Villora-Picó, J. J., González-Arias, J., Baena-Moreno, F. M., & Reina, T. R. (2024). Renewable Carbonaceous Materials from Biomass in Catalytic Processes: A Review. *Materials*, *17*(3), 565.
4. Sheth, K. (2024). Harnessing Nature's Building Blocks: Exploring Sustainable Biomass for Polymer and Composite Materials.
5. Vaishnavi, B. J., & Shanbhag, G. V. (2024). Catalytic hydrogen generation from biomass and its derivatives. In *Handbook of Emerging Materials for Sustainable Energy* (pp. 547-568). Elsevier.
6. Akhtar, M. N., Riaz, S., Ahmad, N., & Jaseer, E. A. (2024). Pioneering Aromatic Generation from Plastic Waste via Catalytic Thermolysis: A Minireview. *Energy & Fuels*.
7. Abdullah, M. A., Nazir, M. S., Hussein, H. A., Shah, S. M. U., Azra, N., Iftikhar, R., ... & Hung, Y. T. (2024). New perspectives on biomass conversion and circular economy based on Integrated Algal-Oil Palm Biorefinery framework for sustainable energy and bioproducts co-generation. *Industrial Crops and Products*, *213*, 118452.
8. Mahajan, P., & Sharma, M. (2024). A comprehensive review on developments and future perspectives of biopolymer-based materials for energy storage. *Energy Storage*, *6*(4), e634.
9. Jeong, D., Kwon, D. S., Won, G., Kim, S., Bang, J., & Shim, J. (2024). Toward Sustainable Polymer Materials for Rechargeable Batteries: Utilizing Natural Feedstocks and Recycling/Upcycling of Polymer Waste. *ChemSusChem*, e202401010.
10. Yang, Z., Ge, Q., & Zhu, X. (2024). Heteroatom Lewis acid zeolites: synthesis, characterization and application in conversion of biomass-derived oxygenates. *Green Chemistry*.
11. Lam, C. V., Vy, D. N. C., Duyen, N. H. K., Xuan, N. T. T., Trinh, T. T., Linh, N. H. G., ... & Hieu, N. H. (2024). Zinc oxide-doped carbon aerogel derived from bagasse cellulose/sodium alginate/zinc nitrate composite for dye adsorption, storage energy and electrochemical sensing. *Journal of Chemical Technology & Biotechnology*, *99*(1), 279-293.
12. Singh, M., Cha, D. C., Kim, H., Park, J., Kim, S., Yoo, C. G., ... & Lee, S. (2024). Photocatalysis-Derived Biomass Conversion for Green Hydrogen Production. In *Towards Sustainable and Green Hydrogen Production by Photocatalysis: Insights into Design and Development of Efficient Materials (Volume 2)* (pp. 47-78). American Chemical Society.
13. Swaminaathan, P., Saravanan, A., & Thamarai, P. (2024). Utilization of bioresources for high-value bioproducts production: Sustainability and perspectives in circular bioeconomy. *Sustainable Energy Technologies and Assessments*, *63*, 103672.
14. Devi, A., Bajar, S., Sheikh, Z. U. D., Singh, A., Kotwal, N., Bharti, A., ... & Kothari, R. (2024). A perspective towards sustainable and economically viable approach of waste biorefineries through lignin valorization. *Biomass Conversion and Biorefinery*, 1-25.
15. Kalla, A., Mayilswamy, N., Kandasubramanian, B., & Mahajan-Tatpate, P. (2024). Biochar: a sustainable and an eco-friendly material for energy storage applications. *International Journal of Green Energy*, *21*(7), 1695-1709.
16. Singh, M., Cha, D. C., Kim, H., Park, J., Kim, S., Yoo, C. G., ... & Lee, S. (2024). Photocatalysis-Derived Biomass Conversion for Green Hydrogen Production. In *Towards Sustainable and Green Hydrogen Production by Photocatalysis: Insights into Design and Development of Efficient Materials (Volume 2)* (pp. 47-78). American Chemical Society.
17. Altalhi, T., Luqman, M., & Bwapwa, J. K. (Eds.). (2024). *Sewage and Biomass from Wastewater to Energy: Possibilities and Technology*. John Wiley & Sons.
18. Devi, A., Bajar, S., Sheikh, Z. U. D., Singh, A., Kotwal, N., Bharti, A., ... & Kothari, R. (2024). A perspective towards sustainable and economically viable approach of waste biorefineries through lignin valorization. *Biomass Conversion and Biorefinery*, 1-25.

