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Investigation and Optimization of Innovative Recycling Techniques for Electronic Waste to Maximize Material Recovery

Shivam Purohit[1*], Farah Malik[2*], Anil Kapse[3*]

[1]Department of Environmental Engineering, Desh Bhagat University, Gobindgarh, India
[2]Department of Metallurgical Engineering, Jaggannath University, Jaipur, India
[3]Department of Mechanical Engineering, Madhav University, Sirohi, India
*Email: shivam.p@dbu.ac.in, farah.m@jgu.ac.in, anil.k@mdu.ac.in

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Abstract: The exponential growth of electronic device consumption has resulted in a rapid increase in electronic waste, posing severe environmental, economic, and public health challenges. Electronic waste contains a complex mixture of valuable metals, hazardous substances, and non-degradable polymers, making its management both critical and technically challenging. This study investigates and optimizes innovative recycling techniques aimed at maximizing material recovery from electronic waste streams while minimizing environmental impact. A hybrid recycling framework integrating mechanical separation, hydrometallurgical processing, and selective thermal treatment was developed and experimentally evaluated. The recovery efficiency of critical metals such as copper, aluminum, and precious metals was analyzed alongside energy consumption and secondary waste generation. Process optimization was performed through parametric analysis of operating conditions to enhance recovery yield and process sustainability. Environmental impact assessment and techno-economic evaluation were conducted to examine the feasibility of large-scale implementation. Results demonstrate that optimized hybrid recycling routes significantly outperform conventional recycling practices in terms of material recovery efficiency and environmental performance. The findings provide a comprehensive foundation for sustainable electronic waste management strategies aligned with circular economy principles.

Keywords: Electric Vehicles, Energy Efficiency, Vehicle Modeling, Driving Cycles, Powertrain Simulation

1. Introduction

The rapid advancement of technology and shortened product life cycles have led to an unprecedented increase in electronic waste generation worldwide. Discarded electronic products such as computers, mobile phones, and consumer appliances contain a wide array of materials, including base metals, precious metals, rare earth elements, plastics, and hazardous compounds. Improper disposal of electronic waste poses significant risks to soil, water, and air quality due to the release of toxic substances such as lead, mercury, and brominated flame retardants [1]. At the same time, electronic waste represents a valuable secondary resource reservoir. The concentration of metals such as copper, gold, silver, and palladium in electronic waste often exceeds that found in natural ores. Recovering these materials through efficient recycling not only conserves natural resources but also reduces energy consumption and greenhouse gas emissions associated with primary mining operations [2]. Despite these benefits, global electronic waste recycling rates remain low, primarily due to technological, economic, and regulatory barriers. Conventional recycling approaches rely heavily on informal processing or rudimentary mechanical separation techniques, which often result in low recovery efficiency and significant environmental contamination. Advanced recycling technologies such as hydrometallurgical and pyrometallurgical processes offer higher recovery potential but are energy-intensive and require careful control to prevent secondary pollution [3]. Therefore, there is a pressing need to develop integrated and optimized recycling strategies that balance recovery efficiency, environmental sustainability, and economic viability. This research addresses this need by investigating innovative hybrid recycling techniques designed to maximize material recovery from electronic waste. The study emphasizes process integration, parameter optimization, and system-level evaluation to develop a scalable and environmentally responsible recycling framework. By

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combining experimental investigation with environmental and economic analysis, the research contributes to advancing sustainable electronic waste management solutions.

2. Characterization of Electronic Waste Streams

Effective recycling of electronic waste requires a thorough understanding of its material composition and physical characteristics. In this study, representative electronic waste samples were collected and categorized based on product type and material content. Pre-processing involved dismantling, size reduction, and segregation to isolate key material fractions. Material characterization was performed using a combination of spectroscopic and analytical techniques. X-ray fluorescence analysis was employed to determine elemental composition, revealing significant concentrations of copper, aluminum, iron, and trace precious metals. Polymer components were identified using thermal analysis to assess degradation behavior and suitability for recovery or energy conversion. Particle size distribution analysis indicated that size reduction significantly influences separation efficiency during mechanical processing. Liberation of metal particles from polymer matrices improved with controlled shredding, highlighting the importance of optimized pre-treatment. This characterization phase provided critical input parameters for designing and optimizing downstream recycling processes [4].

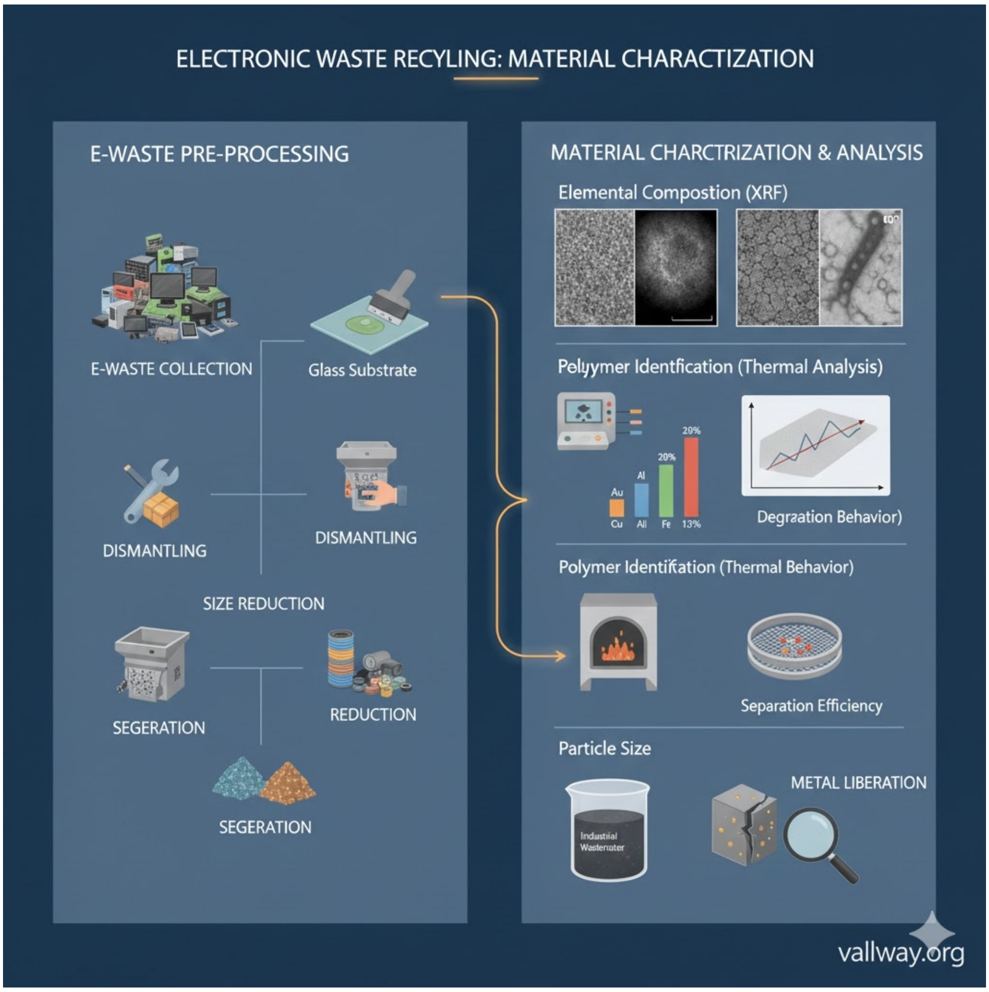

Fig. 1 E-Waste Management

3. Development of Hybrid Recycling Process

The proposed recycling framework integrates mechanical, chemical, and thermal techniques to exploit their complementary strengths. Mechanical separation served as the initial stage, employing shredding, magnetic separation, and density-based classification to concentrate metallic fractions. This step reduced processing volume and improved the efficiency of subsequent treatments. Hydrometallurgical processing was applied to selectively extract target metals using environmentally benign leaching agents. Process variables such as reagent concentration, temperature, and reaction time were systematically adjusted to maximize metal dissolution while minimizing reagent consumption. Selective precipitation and solvent extraction techniques were then used to recover metals in purified form [5]. Thermal treatment was employed selectively to treat residual fractions containing complex composites and hazardous additives. Controlled thermal processes enabled polymer

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decomposition and metal liberation while limiting emissions. Integration of these techniques created a flexible recycling route adaptable to varying electronic waste compositions.

4. Process Optimization and Performance Evaluation

Process optimization focused on maximizing material recovery efficiency while minimizing energy consumption and waste generation. Parametric studies were conducted to identify optimal operating conditions for each process stage. Recovery efficiency metrics were calculated for major metals, and mass balance analysis was performed to evaluate system performance. The optimized process achieved significantly higher recovery rates compared to baseline methods, particularly for copper and precious metals. Energy consumption analysis indicated that integration of mechanical pre-treatment substantially reduced overall energy demand. These results confirm the effectiveness of hybrid recycling strategies in enhancing performance [6].

5. Environmental Impact Assessment

An environmental impact assessment was conducted to evaluate the sustainability of the proposed recycling framework. Indicators such as greenhouse gas emissions, water usage, and secondary waste generation were analyzed. Compared to conventional disposal and recycling practices, the optimized process demonstrated reduced environmental footprint and lower toxic emissions. The assessment highlighted the importance of process integration and reagent selection in minimizing environmental impact. The results support the adoption of advanced recycling technologies as part of environmentally responsible waste management systems.

6. Results and Performance Evaluation

Economic feasibility was evaluated through cost–benefit analysis considering capital investment, operating costs, and revenue from recovered materials. The optimized recycling process exhibited favorable economic performance, particularly when scaled to industrial throughput levels. Sensitivity analysis revealed that metal market prices and process efficiency significantly influence profitability [7].

7. Discussion and Policy Implications

The findings emphasize the need for policy frameworks that support advanced recycling infrastructure and discourage informal processing practices. Incentives for material recovery and extended producer responsibility schemes could accelerate adoption of optimized recycling technologies.

8. Conclusion

This study demonstrates that innovative and optimized hybrid recycling techniques can significantly enhance material recovery from electronic waste while reducing environmental impact. By integrating mechanical, chemical, and thermal processes, the proposed framework achieves superior performance compared to conventional methods. The comprehensive evaluation confirms the technical feasibility, environmental benefits, and economic viability of advanced electronic waste recycling. The research supports the transition toward circular economy-based waste management systems and provides valuable guidance for engineers, policymakers, and industry stakeholders.

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