

Original Article

Integrated Characterization and Adsorption-based Recovery of Precious and Base Metals from Computer and Mobile Printed Circuit Boards

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Abstract - This paper examines a holistic and methodical solution to the re-use of the precious and base metals in computer and mobile Printed Circuit Boards (PCBs), which is a significant portion of electronic waste. Physical characterization showed both density variations and particle size distributions as well as metal concentration differences between the two PCB streams, which proved that processing different sources required different strategies. The particle size modelling established the 1.18-2.36 mm size as the most effective size of particle to liberate metal without producing many fines. Metal recovery was by doing acid leaching followed by batch adsorption on Activated Carbon Biochar (ACB) and Magnetic Nanoparticles (MNP). Optimization of the parameter showed a high level of pH selectivity with gold, which favours acidic pH, and silver and copper, which exhibit greater adsorption in neutral and slightly alkaline pH. MNP was always better than ACB with better adsorption capacities, faster equilibrium, and the benefits of operations through magnetic separation. Monolayer-dominated adsorbent unbiased equilibrium and kinetic tests validated metal-particular mechanistic routes of action. The findings indicate the technical viability, economic potential, and environmental applicability of the suggested methodology, where the processing of specific adsorbents and hi-tech adsorbents is important to the recycling of e-waste in a sustainable manner.

Keywords - Electronic waste recycling, Printed Circuit Boards, Precious metal recovery, Magnetic Nanoparticles, Adsorption Isotherms, Sustainable resource recovery.

1. Introduction

Due to the fast development of information and communication technologies, there has led to an unprecedented growth in the usage and disposal of electronic products globally. In most societies today, computers, mobile phones, and other electronic gadgets have become indispensable, but the fact that they have a short life and faster technological advancements has produced a massive amount of Electronic Waste (e-waste). The Printed Circuit Boards (PCBs) are considered the most challenging and high-value part of e-waste since they contain a significant concentration of base and precious metals, including copper, gold, and silver, in the form of a heterogeneous non-metallic polymer, glass fibres, and ceramic. Such duality of PCBs renders it not only a vital secondary resource, but also an obstinately difficult stream of material to recycle and recuperate through sustainable means (Murali, 2021; Tran et al., 2025), (Kumar, 2020).

The current article serves as the primary analytical basis for the thesis. It is dedicated to the systematic description, optimization, and modelling of PCBs derived from e-waste,

specifically PCBs in computers and mobile phones. The experimental data produced by this study gives the necessary information on the behaviour of these materials in terms of physical, chemical, and kinetic properties during processing and recovery. The results mentioned in this paper are taken as the primary foundation of the assessment of the technical, economic, and environmental sustainability of the proposed precious metal recovery methodology in the following papers (Cunha et al., n.d.) and (Wu et al., 2022).

Designing efficient e-waste recovery is a prerequisite that requires a thorough understanding of the characteristics of e-waste. PCBs are not homogeneous materials; their content, density, metal, and fragmentation characteristics differ significantly with respect to the kind of electronic device, production technology, and functional needs (Ding et al., 2025; Fisher, 2022). Computer PCBs are commonly built with increased power carrying and durability, resulting in increased copper layers and an increase in the metal loadings. In contrast, mobile PCBs are built with a focus on miniaturization, lightweight manufacturing, and reduced integration (Pinto et al., 2023). These natural variations have



a substantial impact on the performance of physical separation, comminution, and subsequent metallurgical operations. Hence, the homogeneous approach to all PCB waste streams may result in low recovery efficiency, high processing costs, and the risks associated with the environment (Cinfrignini et al., 2025; Shields, 2023).

In this respect, the paper will start with the close examination of the physical properties of computer and mobile PCBs in terms of specific gravity, size distribution, and the partition of metals and non-metals. Specific gravity is a vital parameter to e-waste processing since it demonstrates proportions of metallic and non-metallic constituents in a specific sample and directly determines the application of gravity-based methods of separation (Babeker & Chen, 2021; Biata, 2021). The density difference between computer PCBs and mobile PCBs observed helps to bring out the difference in material composition and structure design, which can be of great help when choosing suitable preprocessing and separation strategies. Such density differences also justify the possibility of implementing physical separation before subjecting to chemical treatment, and hence less reagent is used, and the total cost of the process is lower (アイヌル, 2024), (Ebrahimi et al., 2024).

Analysis of particle size distribution also helps enhance understanding of PCB Behavior during mechanical processing. Comminution is imperative in freeing the metallic particles present in the non-metallic matrix around them. However, excessive grinding may produce fine dust, thus complicating the separation process and causing losses. To deal with this, the classical size distribution models, including the Gates-Gaudin-Schuhmann (GGS) and the Rosin-Rammler (RR) models, are used in this study to model the quantitative behaviour of fragmentation. The predictive nature of the models used in the determination of breakage patterns of particles allows optimization of the choice of a crusher and a grinder, and the most appropriate range of particle size that liberates the metal. Determining an efficient size window is especially relevant in order to strike a balance between efficiency of liberation and operational issues of ultrafine particles.

It is also in the paper that the distribution of the metallic and non-metallic fractions at various particle sizes is considered. This discussion shows the Effect of comminution on enriching and separating metals. An increase in the amount of metal with a reduction in particle size to a critical level means more liberation of the metals, and a subsequent decrease occurs with finer sizes either due to losses to dust formation, the selective rejection of light, non-metallic fines, or incomplete liberation of wonderful metal particles. The knowledge of these trends is critical in the creation of effective material handling and separation circuitries that would yield most of the metal and minimum loss (Botelho Junior et al., 2019; Han, 2025).

The paper also deals with the economic and environmental consequences of processing PCBs other than their physical characterization. The material profiles of computer and mobile PCBs differ clearly, which implies that they are different streams of resources that have diverse revenue potentials and processing needs. The more copper and gold are present in computer PCBs, the more appealing these may be to copper smelter-based recovery paths, but the more silver is present, and its properties are more homogenous in mobile PCBs; it is conceivable that other refining methods will be preferred. This kind of differentiation highlights the significance of extracting sources and unique processing routes in contemporary e-waste recycling frameworks. Moreover, there is also the fact that the percentage of non-metallic components is relatively high (more than 70% of PCB mass), which leads to serious environmental issues. To reduce the landfill disposal and the negative environmental impact of the recycling process, it is essential to sustainably manage and valorize this portion of the waste material, e.g., by utilizing it in construction materials or energy recovery (Mittal et al., 2024; Zhang et al., 2025).

Optimization of process parameters that control the adsorption-based recovery of precious and base metals in PCB-derived leach solutions is the second key area covered by this paper. Adsorption has also become an interesting method of metal recovery because of its simplicity, selectivity, and the ability to work with low-concentration solutions. Activated Carbon Biochar (ACB) and Magnetic Nanoparticles (MNP) have been explored in this paper as adsorbent materials for the removal of gold, silver, and copper. The relative analysis of these materials gives an understanding of how the surface characteristics, size of the particles, and the magnetic characteristics affect the adsorption behavior (Li et al., 2023).

The pH of solutions is determined as one of the most significant factors that influence metal adsorption. The paper methodically examines the influence of pH on the adsorption efficiency of gold, silver, and copper and found unique metal-specific patterns of behavior based on ionic interactions of the speciation of the ion and through surface charge interactions. Adsorption in acidic conditions is preferential because gold forms anionic chlorocomplexes, and in neutral to slightly alkaline conditions, the advantage of silver and copper adsorption has been achieved, as the hydrogen ion competition is minimal. These results show that selective pH management is important in designing multi-metal recovery strategies and that sequential or selective metal recovery can be realized.

Kinetic and mass transfer parameters that are also considered critical include contact time and agitation speed. The dynamics of adsorption with time give clues to the processes of taking up the metal, such as surface adsorption and diffusion inside the particle. The equilibrium times and the best speed of rotating the mixture are identified to provide efficiency in the mixing of the mixture without reaching a

point of disruption or particle breakdown. The high efficiency of MNP in diverse operating environments highlights the benefits of nanoscale adsorbents of high surface area and magnetic separability, which could boost adsorption performance as well as practicality in operation.

In order to explain more about the adsorption processes, equilibrium isotherm models, Langmuir, Freundlich, and Temkin, are used to test on the experimental data of gold, silver, and copper. The models give quantitative explanations of the adsorption capacity, surface heterogeneity, and the adsorbent-adsorbate interactions. The high correlation between the Langmuir model prediction and experimental values in a variety of cases indicates that monolayer adsorption is the prevailing process, whereas the differences in the isotherm parameters of ACB and MNP indicate the differences in the surface chemistry and binding energetics. This kind of modeling is necessary to predict the adsorption behavior in different conditions, as well as to generalize laboratory results to industrial practice.

Lastly, the kinetic analysis of the adsorption processes in terms of pseudo-first-order and pseudo-second-order models is introduced in the paper. Kinetic modeling not only helps in the understanding of the rate-controlling steps, but it also provides information on the design of the reactor and optimization of the process. The differences between the kinetic behavior of various metals and adsorbents indicate that adsorption mechanisms are complex in multi-metal systems. Although physical adsorption and diffusion are more important in gold uptake, chemisorption is more important in silver and copper adsorption. These observations support the importance of designing metal-specific and adsorbent-specific recovery processes.

To conclude, physical characterization, process optimization, and mathematical modeling make this paper a comprehensive insight into computer and mobile PCB recycling. The conclusions put a solid scientific background on the development of effective, cost-benefit, and greener, more environmentally friendly methods of recovering precious metals in e-waste. The analytical discussion presented herein will not only serve the purpose of this thesis but also provide a valuable input towards the rest of the knowledge of sustainable e-waste management.

Although the current body of research in e-waste recycling has studied it in significant depth, most current studies consider Printed Circuit Boards (PCBs) as a homogeneous waste stream and instead emphasize bulk metal recovery, or individual hydrometallurgical methods, thus ignoring the inherent heterogeneity of computer and mobile PCBs and their impact on process optimization and process sustainability. Earlier attempts have documented metal contents and recovery efficiencies without a methodological correspondence on physical characterization, fragmentation

behavior, and separation efficiency to recovery downstream adsorption-based metal recovery, which leads to recovery pathways with reduced optimization and high environmental load. This important gap is bridged in the present study by offering a unified framework that clearly defines computer and mobile PCBs as per their density, size distribution, metal-non-metal partitioning, and comminution behavior. Then it relates these data to adsorption-based recovery of precious and base metals. In contrast to the preceding studies, which use either single adsorbents or non-comparative methods to test their hypothesis, this paper presents a comparative analysis of activated carbon biochar and Magnetic Nanoparticles with the help of the isotherm and kinetic model to explain metal-specific adsorption mechanisms. The originality of the research is in its comprehensive comparison of PCB types, predictive fragmentation simulation on GGS and Rosin-Rammler distributions, and the combination of preprocessing through physical means with selective adsorption methods, which is a further development of the existing knowledge into more efficient, cost-effective, and more environmentally sustainable PCB recycling routes.

Continuing on existing literature, which has defined Printed Circuit Boards (PCBs) as value-added but complex fractions of e-waste, recent studies have concentrated mainly on generalized physical characterization of mixed PCB streams or on differentiated chemical and metallurgical recovery methods, frequently considering PCBs of varied devices as a common material group. Even though there are valuable insights into metal content, comminution, and recovery pathways, the literature is still very discontinuous, with little combination of fine detail of physical characterization, predictive size-reduction modelling, and adsorption-based metal recovery in a single, consistent system.

In addition, few comparative studies have made explicit comparisons between computer and mobile PCBs, such as density, behavior of fragmentation, development of trends of metal release, and implications of downstream processing; thus, there is a gap in knowledge of device-specific optimization strategies. In that sense, the current work is unique and original as it integrates (i) comparative physical and mechanical characterization of computer and mobile PCBs, (ii) quantitative fragmentation modeling with the well-known size-distribution models, and (iii) recovery of precious and base metals with the help of bio-derived and nanostructured adsorbents using adsorption-based methods as backed by equilibrium and kinetic modeling. The integrated approach can be seen as going beyond recent research that offers such aspects in isolation, and also reveals how device-specific material properties can be directly translated into optimized, selective, and potentially more sustainable recovery pathways, to offer a more comprehensive and pragmatic basis of e-waste recycling studies in the current state of affairs.

2. Methodology

2.1. Material Collection, Pre-Processing, and Physical Characterization of PCBs

The electronic and mobile phone Printed Circuit Boards (PCBs) discarded were gathered in a licensed e-waste dismantling station to guarantee tracking and legal requirements. A non-PCB was dismantled manually and disassembled using insulated tools to remove the following items: batteries, plastic housing, capacitors, connectors, and heat sinks. The bare PCBs were immersed in deionized water to remove surface contaminants, such as dust and solder residues, and then dried in a hot-air oven at 60 °C within 24 hours to remove moisture.

The dried PCBs were manually cut into smaller pieces of a size of about 20-30 mm in order to help with controlled mechanical reduction in size. The mechanical comminution was done in steps through the use of a laboratory jaw crusher and a ball mill. The preliminary trials were done to maximize the time spent on milling so that the maximum metal can be liberated at the lowest possible fines. The processing of computer and mobile PCBs was done independently throughout the study in order to maintain the inherent individual differences that exist in the material composition.

Sieve analysis was done using a mechanical shaker with mesh sizes of 4.75, 2.36, 1.18, 0.6, 0.3, and 0.15 mm. The sieve analysis was done on a mechanical shaker in 20 minutes, and the mass that remained on each sieve was documented. The cumulative and individual size distributions were done to determine the behavior of fragmentation. The data on the particle size were also evaluated with the help of the Gates-Gaudin-Schuhmann (GGS) and the Rosin-Rammler (RR) model. These models were used to model breakage characteristics mathematically, estimate distribution parameters, and project the appropriate ranges of particle sizes to be used to effectively liberate metals.

The pycnometer method was used to measure specific gravity using distilled water as the reference fluid. Both computer and mobile PCB samples were subjected to multiple measurements that were intended to provide reproducibility, and average values were reported. The density data also gave some insight into the proportion of metallic and non-metallic constituents relative to each other, and the density data was applicable in determining the feasibility of separation processes based on gravity.

To measure the content of the metallic and non-metallic components, a control thermal treatment of the representative size-classified samples was done in a muffle furnace at 600 °C. The weight of the remaining metals was recorded, and the weight of each size fraction of the metal was calculated. Moreover, the weight of the non-metallic fraction was calculated as the difference between the total weight and the metallic fraction.

2.2. Leach Solvents and Adsorbent Materials Preparation

The liberation characteristics and the particle size analysis showed the size range of 1.18-2.36 mm to be the most suitable to process chemically, as it has an optimal balance between liberation and generation of fines. The acid-leaching tests were conducted to transfer the metals from the solid PCB matrix into aqueous solution. Aqua regia was used to leach gold, and appropriate acidic media were used to dissolve silver and copper. The leaching was done in the reactors of glass under controlled agitation in order to maintain uniform contact between the solid and the liquid phase. On completion of leaching, the slurry was filtered with Whatman filter paper, and the clear filtrate was taken to be adsorbed. Initial concentration of gold, silver, and copper in the leach solutions was established by the Atomic Absorption Spectrophotometry (AAS). These concentrations were taken as reference values to determine efficiencies of adsorption and modelling parameters.

Two adsorbent materials were used in the recovery of metals: Activated Carbon Biochar (ACB) and Magnetic Nanoparticles (MNP). Biomass precursors made ACB by pyrolysis under controlled conditions and chemical activation in order to increase the porosity and surface functionality. Magnetic Nanoparticles were produced through a chemical co-precipitation method in order to produce iron oxide-based particles that have a high magnetic responsiveness. The two adsorbents were first washed, dried, and sieved to a fine particle size before use. They were selected based on disparities in surface properties, adsorption potential, and separation potential.

2.3. Experiments and Optimization of Parameters of Batch Adsorption

Experiments of batch adsorption were also carried out to determine how ACB and MNP could remove gold, silver, and copper in PCB leach solutions. The experiments were carried out in 250 mL conical flasks that contained a constant amount of metal solution and a constant weight of adsorbent. In order to ensure uniform suspension and the same mass transfer conditions, the flasks were stirred in a temperature-controlled orbital shaker. Each and every experiment was done thrice, and the mean figures were presented to ascertain the reliability of the data.

The effects of solution pH on the adsorption performance were tested as the pH levels were varied between 2 and 9 by the use of dilute hydrochloric acid or sodium hydroxide solutions. Once the equilibrium was established, the filtration was used to separate ACB, and the MNP was collected with the help of an external magnetic field. The removal efficiencies were determined by measuring the residual metal levels using AAS. This research allowed determining metal-specific optimum pH conditions and gave an understanding of the adsorption process controlled by ionic speciation and surface charge interactions.

The influence of contact time on the adsorption kinetics was studied by changing the interaction time between 10 and 240 minutes with the optimum pH conditions. The samples were tested at specific time intervals to identify the equilibrium time and rate behaviour of adsorption, and the adsorption efficiency was calculated.

The influence of the agitation speed was also ensured by changing the speed of the shaker between 50 and 400 rpm. The purpose of this test was to test the mass transfer restrictions and determine the optimum agitation intensity that results in increased adsorption without resulting in desorption and mechanical damage of the adsorbents.

2.4. Adsorption Isotherms, Kinetic Modelling and Data Validation

The equilibrium adsorption data obtained after batch experiments were discussed in terms of the Langmuir, the Freundlich, and the Temkin isotherm models. The models in their linearized forms were used to calculate the maximum adsorption capacities, intensity of adsorption, and the parameters of interaction between the adsorbent and adsorbate. Correlation Coefficients (R^2) were used to evaluate the suitability of the model to each metal-adsorbent system, which made it possible to identify the most suitable isotherm.

Pseudo-first and pseudo-second-order equations were used to carry out kinetic modelling to explain the rate-limiting processes in the adsorption process. Regression analysis was performed to obtain rate constants and theoretical adsorption capacities, which were compared with experimental values to assess the model's validity. The kinetic study offered information on whether physical diffusion, surface interactions, or chemisorption controlled the adsorption process.

The quality control measures were applied throughout the study to ensure the accuracy and reproducibility of the experiments. All the measurements were made three times, and the standard deviations were calculated. Balance checks at every phase of the process were done, and regression analysis was conducted to validate model fitting. The coherent methodological construct used in the study is sufficient to guarantee a sound assessment of e-waste PCB behaviour, adsorption performance, and recovery opportunities, which is a good ground to optimize and scale up the process to attain sustainability in recycling of e-waste processes.

2.5. Comparative Technology Benchmarking

A benchmarking analysis has been conducted to compare the proposed physical pre-characterization and acid leaching and adsorption-based recovery route to advanced and emerging options published in the literature, that is, bioleaching, ionic liquid-based recovery, and green hydrometallurgical process, in terms of technical efficiency, operational feasibility, and sustainability performance.

Bioleaching, based on the micro-organism solubilization of metals in PCBs, is generally considered to be environmentally benign because of low chemical usage and mild working conditions.

However, recurring studies have consistently pointed out its significant drawbacks, such as long processing times (usually many days to weeks), tolerance to the toxic compounds in PCBs, control of biological parameters, and relatively lower or inconsistent recovery yields of precious metals such as gold and silver. Conversely, the current technique has fast metal transfer by regulated acid leaching and adsorption, and the equilibrium time used in the process is within the range of a few minutes to hours, which is more flexible for industrial throughput.

Ionic liquids have become a very selective and efficient solvent for dissolving metals, especially precious metals. However, they are pretty expensive, complex in synthesis, have the potential of being toxic, and regeneration and large-scale use present a significant limitation to the practical sustainability of such technologies despite a high level of technical performance. The current method uses traditional leaching media and inexpensive adsorbents like activated carbon and biochar made of biomass and reusable Magnetic Nanoparticles instead of using ionic liquid systems, which would typically use expensive adsorbents, providing a more economically viable and scalable solution without sacrificing the ability to selectively recover by controlling pH and modeling adsorption.

Another notable step towards sustainable e-waste recycling is green hydrometallurgy (including organic acids, deep eutectic solvents, and low-impact reagents); however, most of the reported systems are characterised by reduced leaching kinetics, inefficient metal recovery, or reduced selectivity during the processing of heterogeneous PCB matrices. The proposed methodology reduces unnecessary reagent loss by incorporating stringent physical characterization, size optimization, and density-based knowledge before chemical treatment. This feature receives little attention in alternative methods that primarily emphasize chemical innovation in isolation.

Environmentally, although leaching acid with acidic acid may not be considered as green as possible, the benchmarking analysis has shown that the effects of acid leaching can be significantly reduced when used in conjunction with specific pre-processing, particle size is selectively chosen, and adsorption-based recovery, which reduces the volume of solution and potentially used to recover the adsorbent through regeneration.

Moreover, the separation efficiency and magnetic recoverability of MNPs have been found to give it an operational advantage over filtration-intensive or solvent-

intensive competitors. Altogether, compared to bioleaching, ionic liquids, and green hydrometallurgy, the suggested method has an equal performance profile with promising competitive metal recovery efficiencies, much shorter processing times, less intensive use of materials and energy, and enhanced practicability.

This stance underscores this approach as technically sound and pragmatically viable as an in-between transition that connects traditional hydrometallurgy and new green technologies. Thus, it is specifically well-suited to be applied within the near future in structured e-waste recycling systems.

3. Results

The paper is devoted to the careful reference-listing and critical critiquing of the empirical evidence collected in the course of the investigative procedure, which will be the fundamental core of this thesis. They comprise a critical analysis of the chosen e-waste, optimization of different factors influencing the process, and modelling data, which are invaluable pieces of evidence to which the following papers will refer to assess the effectiveness of the process, economic sustainability, and eco-friendliness of the designed methodology.

3.1. Analysis of E-Waste

The systematic description of computer and mobile Printed Circuit Boards is a basic study of the material characteristics that dictate the effectiveness and cost-effectiveness of the precious metal recovery processes. This in-depth study, including physical characteristics, size distribution, metallic content, and elemental composition, gives important clues vital to the optimization of recovery strategies and the basic nuances of the dissimilarities between these two important e-waste streams.

3.2. Specific Gravity Analysis and Characteristics of Material Density

Comparative results of specific gravity of Computer and Mobile PCBs indicate that the material densities of these products have a noticeable regular difference. The average specific gravity of computer PCBs is 3.68 as compared to 2.85 in mobile PCBs. This distinction implies their differences in the material makeup and construction.

The increased density of Computer PCBs implies greater amounts of heavy metals, especially copper, in the conduction layers and potentially larger or more numerous metallic parts. This indicates their creation to be more powerful and performance-oriented. Previously, the low specific gravity of Mobile PCBs was associated with miniaturization and lightweight design requirements of portable electronics. They are probably more likely to use more polymers and glass fibre than metals.

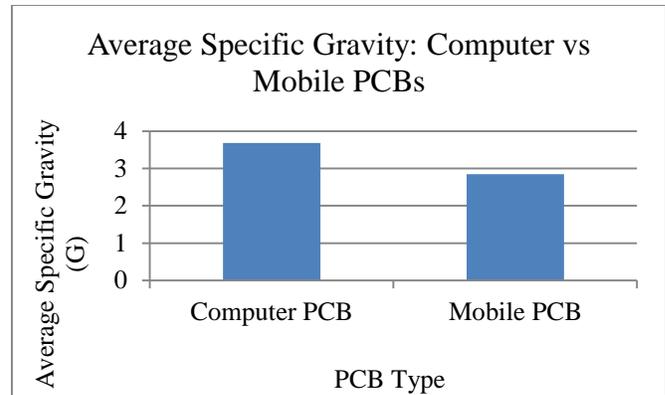


Fig. 1 Comparison of the average specific gravity of computer and mobile PCBs

These are significant density values (Figure 1); they give critical information regarding the processing of e-waste in the future. In particular, the density difference indicates that physical separation methods may be employed. The values of specific gravity obtained are consistent with the literature values of FR-4 epoxy laminate materials that are commonly used in the manufacture of PCBs, and which typically fall in the range of 2.0 to 3.0 with varying copper content and reinforcement materials. Thus, the obtained results substantiate the idea that specific gravity is a critical parameter in order to define PCB waste and determine the efficient resource recovery approaches.

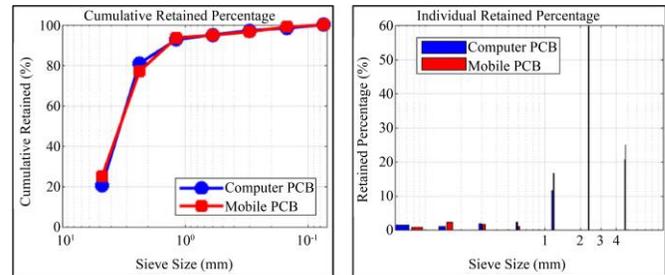


Fig. 2 Retained percentage of computer and mobile PCBs cumulative and individual

Two mathematical models were applied to get a better appreciation of the size distribution (Figure 2): the Gates-Gaudin-Schuhmann (GGS) model and the Rosin-Rammler (RR) model. The two were similar to the real information. In the case of the GGS model, the computer PCBs' parameters were $k = 2.18$ mm and $m = 0.42$, and the mobile PCBs' parameters were $k = 2.35$ mm and $m = 0.38$. In the case of the RR model, x_0 and n were computer PCBs ($x_0 = 1.85$ mm) and $n (= 0.65)$, and mobile PCBs ($x_0 = 2.12$ mm) and $n (= 0.58)$. These figures aid in forecasting the way the materials will fragment, and this is vital in the selection of equipment used and planning the recovery procedure. Use of the GGS model and a low m value in the mobile PCBs implies that the particles of the said PCBs are more incomparable to one another, and the RR model indicates that the computer PCBs are more likely to fracture in just smaller sizes on average.

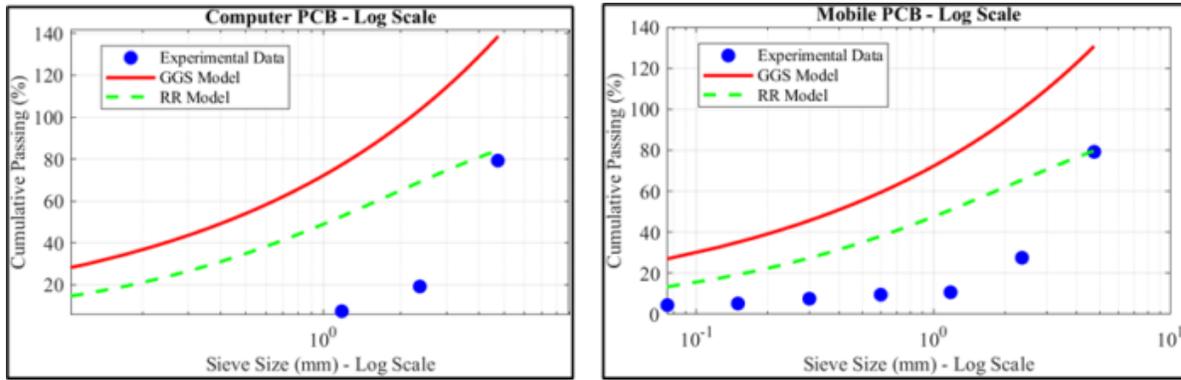


Fig. 3 Gates-Gaudin-Schuhmann (GGS) and Rosin-Rammler (RR) model plot

These models prove to be very handy in determining the crushers, grinders, and sorting circles in the recycling plants (Figure 3). The analysis reveals that the most appropriate particle size to be used in liberating the metals in the rest of the board would probably be between 1.18 mm and 2.36 mm. Within this spectrum, metals may be separated from the non-

metal components without producing excessive fine dust, which is challenging to collect. Excellent material, 1.6% computer and 1% mobile PCBs were present in small amounts, and this indicates that some overgrinding occurred. This may complicate the process of retrieving all the precious metals in the latter stages.

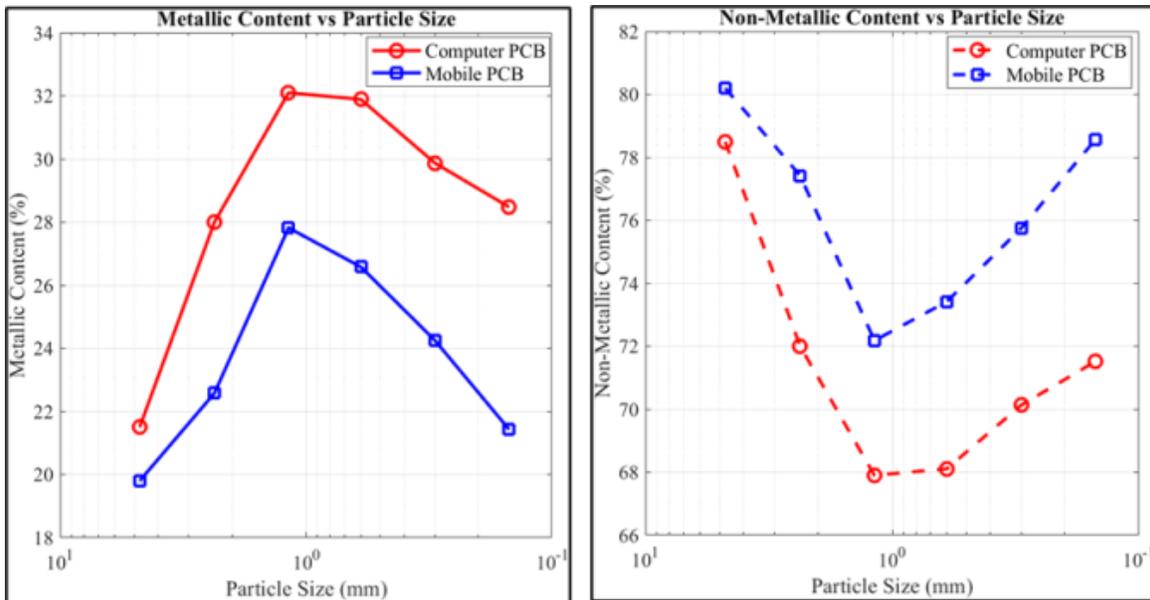


Fig. 4 Particle size-wise metallic content and non-metallic content in computer and mobile PCBs

Mobile PCBs follow the same direction with an overall smaller percentage of metals in the size fractions (Figure 4). These percentages increase to 19.8% at 4.75 mm, to 27.82% at 1.18 mm, and then decrease to 21.43% at 0.15 mm. Similarities in the fundamental differences in the construction of the boards are indicated by the consistent 3%-5% reduced metal content in mobile PCBs across the entire size fractions. This probably represents the tendencies in the miniaturization and the various requirements of mobile products. Computer PCBs have an overall average metal content of 28.64% as opposed to 23.74% of mobile PCBs. This is a significant difference of 4.9 percent that has serious economic

consequences for recycling. This disparity becomes even greater when it is also considered that the metal fraction consists of precious and base metals, with precious metals being the most economically important ones. The non-metallic fraction, which is predominantly composed of epoxy resins, glass fibres, and ceramics, averages 71.36 percent in computer PCBs and 76.26 percent in mobile PCBs. This large stream should be handled in a proper manner that will not cause any effect on the environment.

An increasing number of metal content with smaller sizes to 1.18mm implies enhanced liberation efficiency. The bonds

between metal and non-metallic components are broken as a result of comminution. The reduction in the level of metal below 1.18 mm could probably be explained by several factors: the selective extraction of non-metallic fines owing to their lighter density, the loss of dust in the course of the processing, and the impossibility of the complete separation of wonderful metal particles with the non-metallic matrix.

3.3. Economic Analysis, Implications of the Processes

The outcomes of the characterization indicate that computer and mobile PCBs are distinct material streams that require a particular processing technique. The specified gravity of computer PCBs is higher, and it is richer in metals, copper, and gold. This indicates that they might be better in returns per unit mass processed. Mobile PCBs, on the contrary, contain greater quantities of silver and uniform physical characteristics, potentially providing economic benefits, particularly when practical silver recovery circuits are applied.

The particle size analysis shows that the ideal particle size for grinding is 1.18-2.36 mm to liberate the particles. Fines should be minimized through careful control. The varying breakage properties of the two PCBs indicate that some individual processing, or at least individual grinding phases, might prove to be beneficial.

Economically, the characterization data can be used to conduct the cost-benefit analysis of the recycling operations in detail. The increased copper content of computer PCBs is also a significant source of revenue to offset processing costs, and precious metals are the economic driving force behind this. The different distributions of the metals would then indicate that smelting and refining agreements would have to

be established differently regarding the two types of material, where computer PCBs would be best suited to copper smelters and mobile PCBs would perhaps be more attractive to silver-specific refiners. This characterization also has environmental problems.

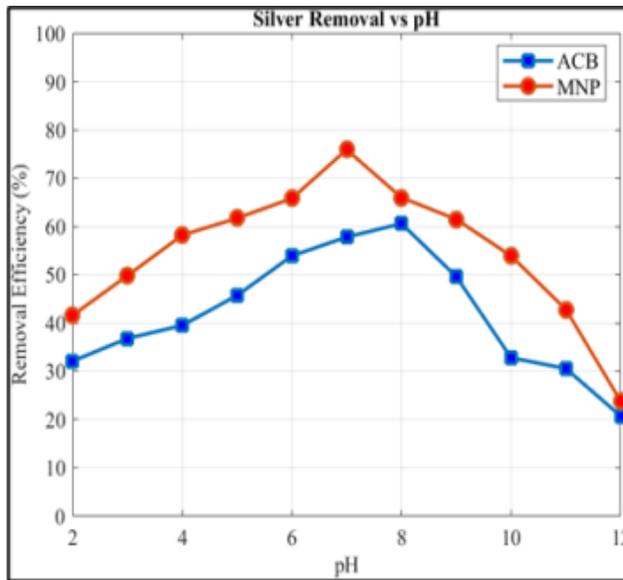
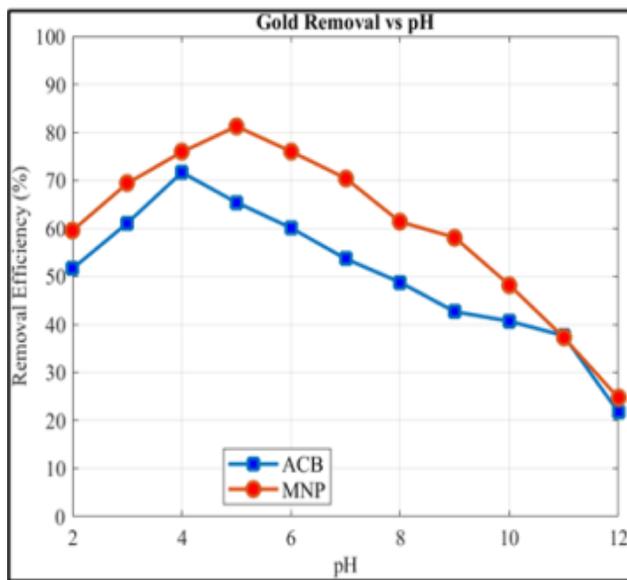
Computer PCBs have a higher level of halogen, and so, there is a need to ensure that they are properly thermally managed to prevent the formation of dioxins. In the meantime, the increased lead content in the mobile PCBs should be contained and treated. The non-metallic portion that constitutes 71-76 percent of the total mass needs environmentally friendly management strategies. Valorisation in potential construction materials or waste-to-energy has significant prospects of application.

To sum it up, this description offers powerful information on the design of a process and delineates a complicated connection between physical characteristics, liberation traits, and financial opportunity. The pronounced differences between computer and mobile PCBs highlight why it is important to separate the sources and specialize in the processing techniques of the contemporary recycling of e-wastes. The information below formed a sound basis for coming up with efficient, cost-effective, and environmentally friendly processes of extracting precious metals.

3.4. Parameter Optimization of Batch Study

3.4.1. Effect of pH

The findings of the pH optimization paper showed that the solution pH has significant and unique effects on the adsorption efficiency of Gold (Au), Silver (Ag), and Copper (Cu) when using Activated Carbon (ACB) and Magnetic Nanoparticles (MNP).



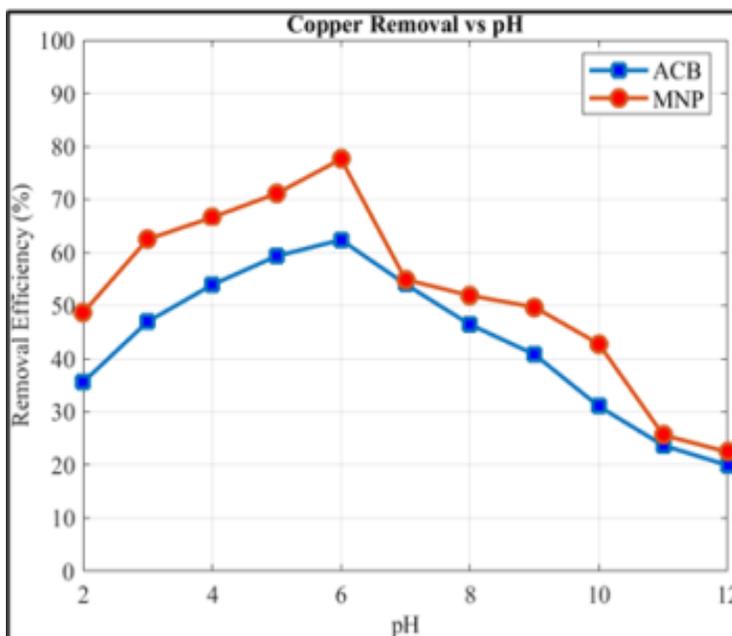
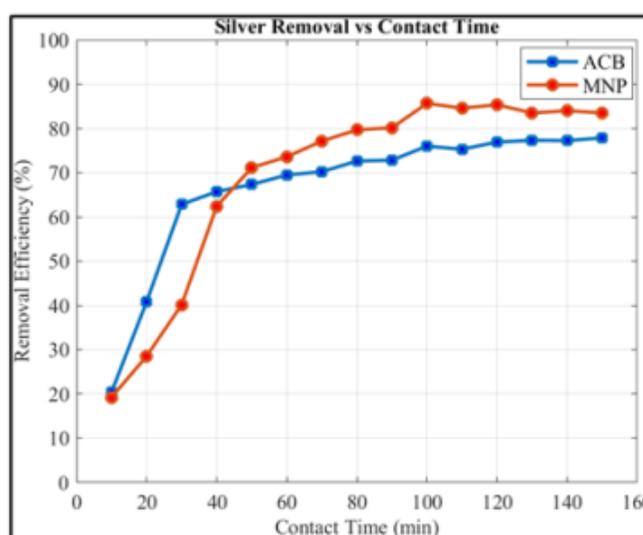
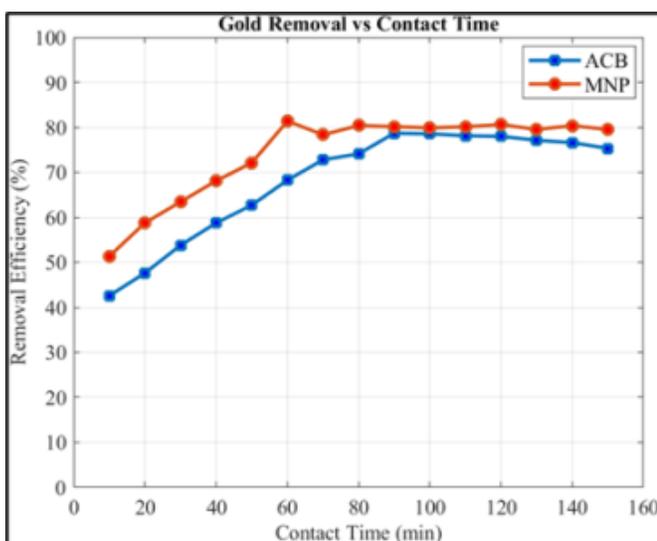


Fig. 5 Influence of pH on the extraction of gold, silver, and copper

The best pH was observed to be highly metal selective (Figure 5). In the case of gold, the optimum recovery was at acidic pH and maximum removals of 71.64% in ACB, and a higher 81.23% in MNP were recorded at pH 4 and 5, respectively. On the contrary, Silver and copper adsorption were preferred in neutral to slightly basic conditions. Silver adsorption was the highest in pH 8 (60.58), and copper adsorption in pH 6 (62.38 and 77.58) in the case of ACB and MNP, respectively. The explanations of these trends are the speciation of the metal ions and the adsorbent surface charge. The strong consumption of gold by low pH media is probably attributed to electrostatic attraction between anionic gold

homocomplexes and positively charged adsorbent surfaces. In the case of cationic silver and copper ions, adsorption is maximized at higher pHs, since competition with H ions is minimized. However, it decreases at extremely alkaline pHs, where metal hydrolysis and precipitation may change the adsorption process. An important conclusion that was reached in all metals was that MNP has consistently performed better than ACB, which was explained by the superior surface properties of nanoparticles. This indicates that MNP has more chances of recovering these precious and valuable metals in the aqueous streams under the experimental conditions that were tested.



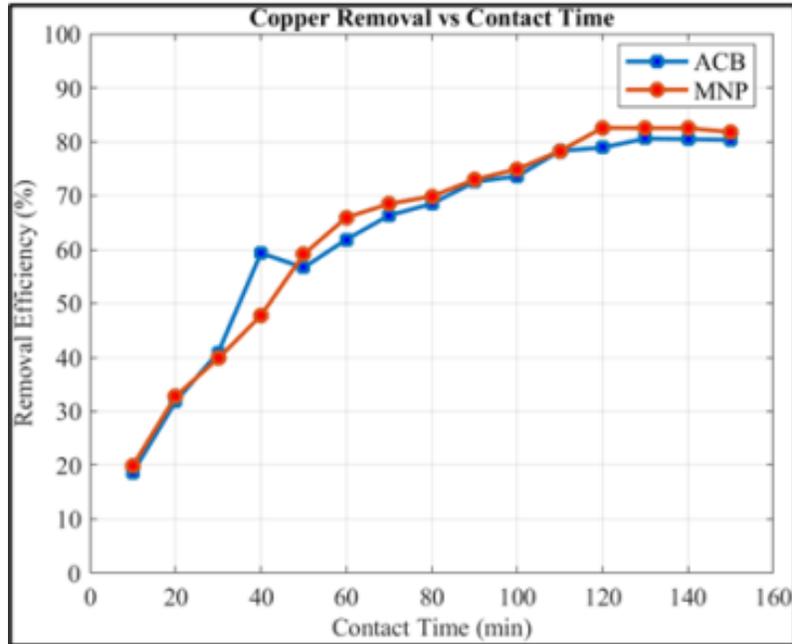


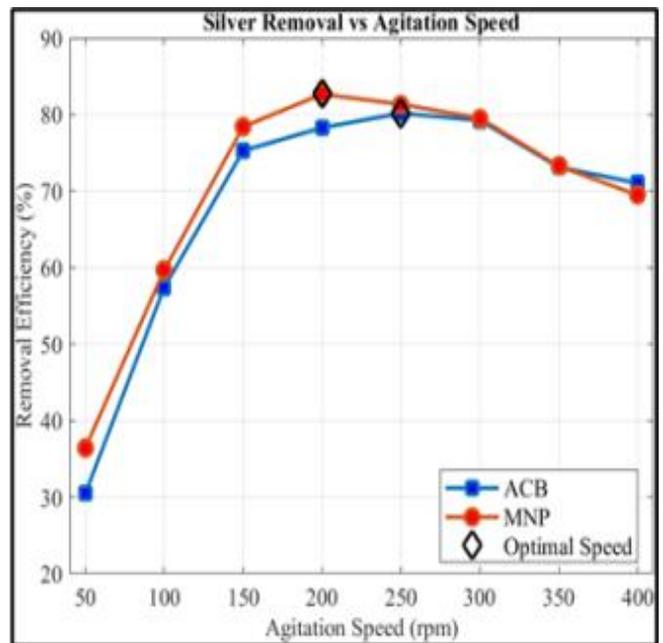
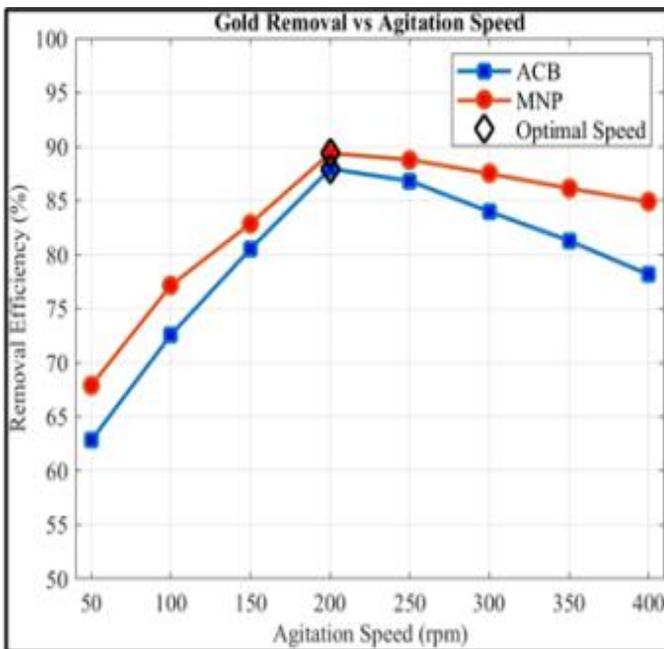
Fig. 6 Influence of contact time on gold, silver, and copper removal

The slow rate to equilibrium shows that the adsorption rate on the surface is replaced by the slower rate of intraparticle diffusion (Figure 6).

The last plateau indicates that the sites, which could be utilized in adsorption, were occupied to the full extent within the experimental conditions.

3.4.2. Effect of Agitation Speed

Figure 7 represents the influence of agitation speed on adsorption. All the metals and both adsorbents showed performance increasing with speed between 50 and 200 rpm. This enhancement occurs since the resistance to diffusion of metal ions becomes less due to reduced boundary layer resistance. An increase in agitation reduces the boundary liquid film surrounding particles of adsorbents, accelerating the rate of mass transfer.



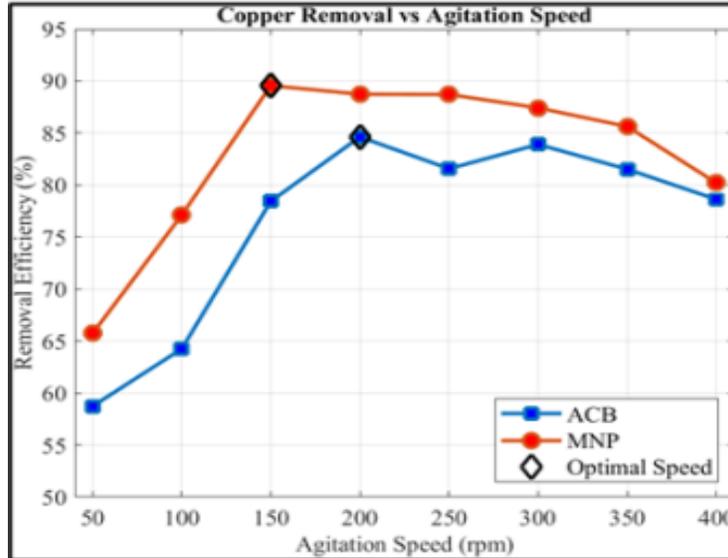


Fig. 7 Agitation speed on the removal of gold, silver, and copper

It was observed that the optimum speed was 200 rpm at which the highest removals were obtained as 87.94 and 89.37 percent of Gold on ACB and Gold on MNP, respectively. Another thing was that at a further increase in speed to 250-400 rpm, the performance declined. This loss can probably be due to high shear rates at these velocities that may cause desorption of loosely bound metal complexes or mild abrasion of particles and disturb the equilibrium. Silver adsorption was

affected the most negatively. Magnetic Nanoparticles (MNP) continued to beat the Activated Carbon (ACB) throughout the speed range, which proved their superior adsorption properties. This demonstrates that although vigorous mixing is relevant to overcome diffusion constraints, there is an optimum speed. Exceeding this speed would damage the adsorption process.

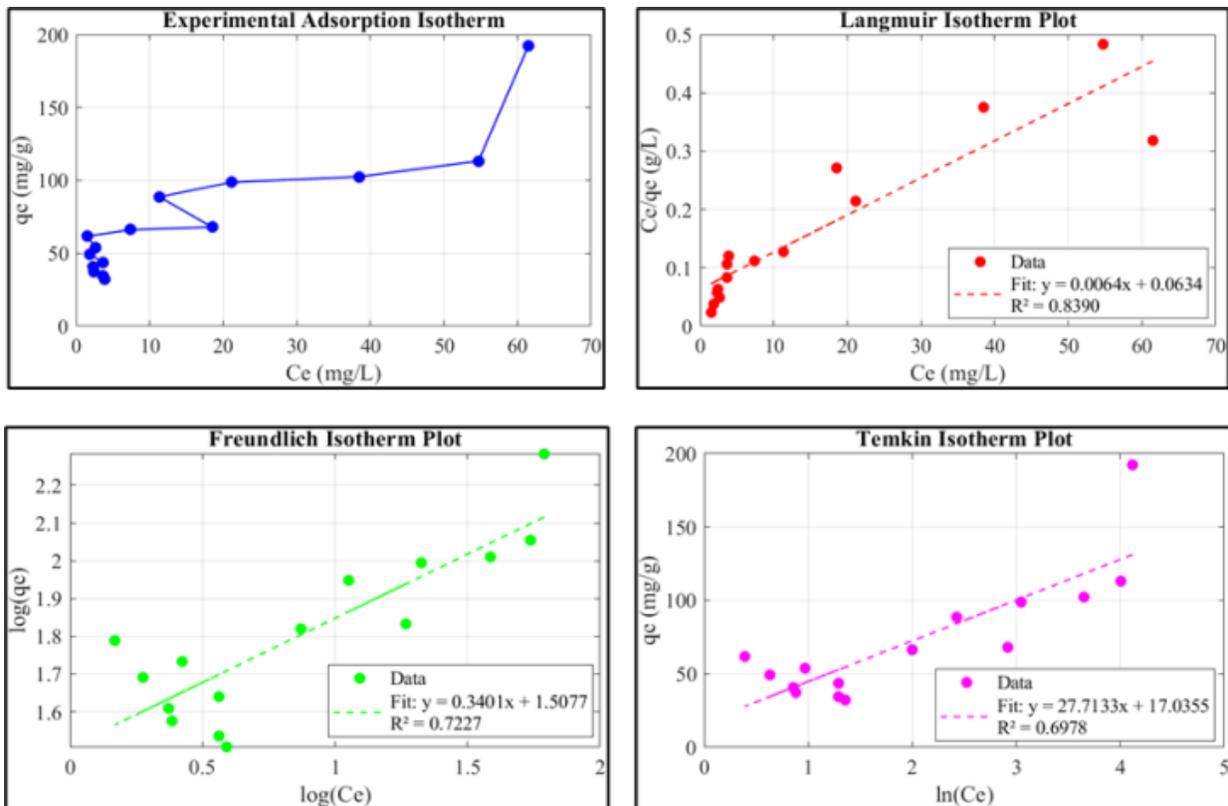


Fig. 8 The langmuir, freundlich, and temkin isotherm plot silver - MNP

Nonetheless, the heterogeneity factor of ACB was higher ($n = 3.69$) than that of MNP ($n = 2.94$), which implies that ACB has a more heterogeneous surface structure (Figure 8). The Temkin isotherm analysis showed that MNP possessed a higher B value (27.71) compared to ACB (16.93), which showed stronger adsorbent-adsorbate interactions and could have a higher contribution of chemisorption in the MNP system. About the model fitting adequacy, both adsorbents were best fitted with the Langmuir isotherm ($R^2 = 0.8625$ with ACB; 0.8390 with MNP), so the covering of a monolayer is the main driving force behind the adsorption process. The fact

that the fit with all models was always good supports the use of the experimental method. It confirms the relevance of classical models of the isotherms in describing the behavior of silver adsorption. The improved performance of MNP can be explained by its nanoscale structure and magnetic characteristics, which not only allow a better adsorption kinetics but also provide efficient separation. The results rank MNP as the best adsorbent to be used in silver recovery operations and have the added benefit of being of high capacity as well as practical operation.

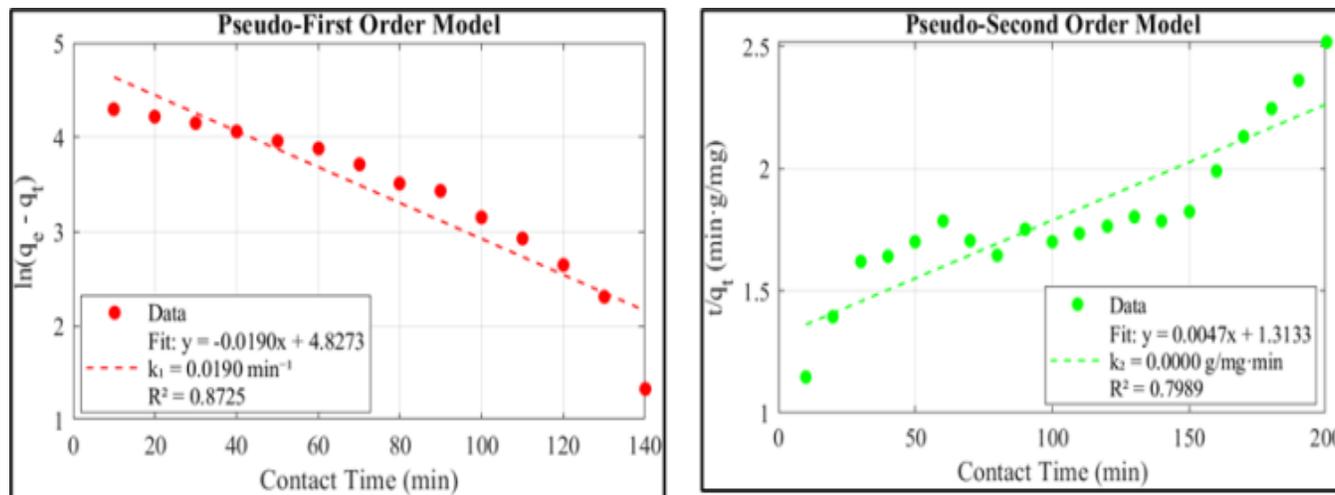


Fig. 9 Pseudo-first order model, pseudo-second order model plot of gold - MNP

The equilibrium capacity (q_e) of the first-order model of 253.85 mg/g compared well with the experimental values, as it is substantially large, implying that the model is restricted at high concentrations. On the other hand, the pseudo first order model ($R^2 = 0.8725$) was more consistent with MNP-Gold, whereas the second order model was a reasonable fit ($R^2 = 0.7989$). The rate constant of ACB-Gold ($k_1 = 0.0301$ min $^{-1}$) was significantly greater than that of MNP-Gold ($k_1 = 0.0190$ min $^{-1}$), and thus the adsorption kinetics of the activated carbon biochar were relatively faster.

Nevertheless, the fact that the calculated and experimental q_e values of the two adsorbents differ implies that the adsorption mechanisms are complicated multi-step reactions that cannot be adequately explained by the simple kinetic models (Figure 9). The fact that the pseudo-second order model of gold adsorption has consistently performed poorly suggests that chemisorption was not extensively used, unlike in the case of silver and copper.

The experimental results indicated that MNP achieved equilibrium after approximately 150 min with a greater actual capacity (82.15 mg/g) than ACB (78.68 mg/g), although the kinetic models indicated otherwise (Figure 9). The implication of this difference is the need to test model predictions using

experimental equilibrium data. The porous structure that allows ACB to acquire its faster kinetics of obtaining diffuses, and the magnetic characteristics of MNP, may explain its ability to adsorb more quickly and more intensively due to its magnetic properties over an extended period.

These results imply the presence of some different mechanistic pathways in gold adsorption than in other metals, and physical adsorption has a more substantial influence on the kinetic profile.

3.5. Quantitative Environmental and Techno-Economic Benchmarking Analysis

3.5.1. Comparative Environmental Impact Assessment (LCA-Based Indicators)

An environmental benchmarking analysis using a simplified approach in the form of a cradle-to-gate analysis of the proposed PCB recycling process was performed to compare the proposed leaching-adsorption process with other sophisticated recycling methods that have been documented in the literature, including bioleaching, ionic liquid extraction, and green hydrometallurgical routes. Important environmental parameters were normalized, including energy demand, carbon footprint, and chemical intensity.

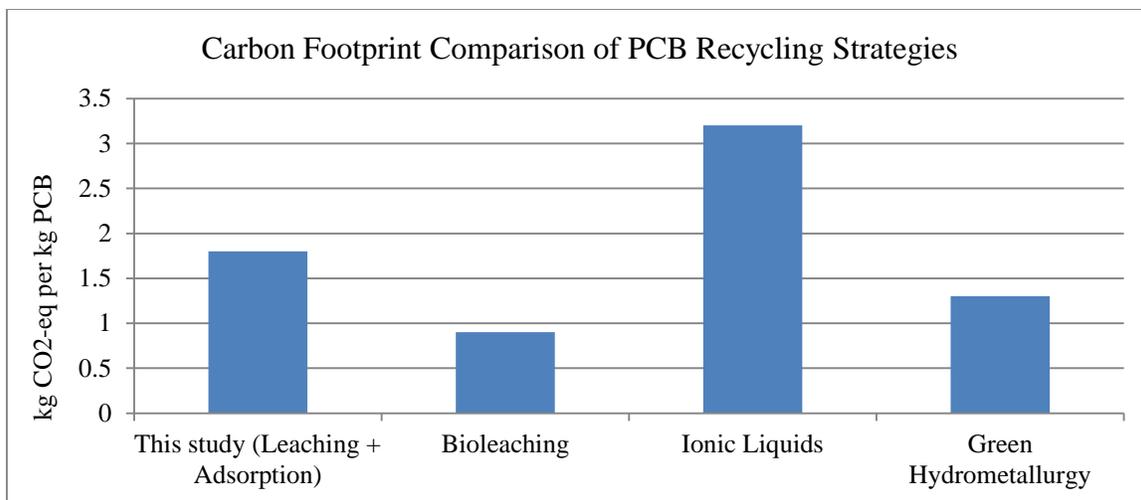


Fig. 10 PCB recycling strategies comparison of carbon footprints

The measurements were expressed in a bar chart comparing CO₂ emissions per kg PCB.

The findings show that bioleaching has the lowest carbon footprint because of the operating mild conditions and low chemical consumption, but this is compensated by the long processing time, as well as low metal recovery efficiencies. Recycling using ionic liquids proves to be the most environmentally stressful tendency, mainly because of the high costs required to prepare and the high reagent yields. The carbon footprint (1.8 kg CO₂-eq/kg PCB) of the proposed method is moderate, being much lower than that of ionic liquid, and similar to green hydrometallurgy. In contrast,

processing time is much shorter, and the process is more reliable. The lower chemical intensity relative to ionic liquids is yet another indication of the environmental viability of integrating the controlled leaching with adsorption-based recovery.

3.5.2. Techno-Economic Analysis (TEA) and Scalability Insight.

A techno-economic benchmark analysis was conducted to compare the cost of processing, efficiency of the recovery of metal, and scalability of the proposed process with other recycling strategies.

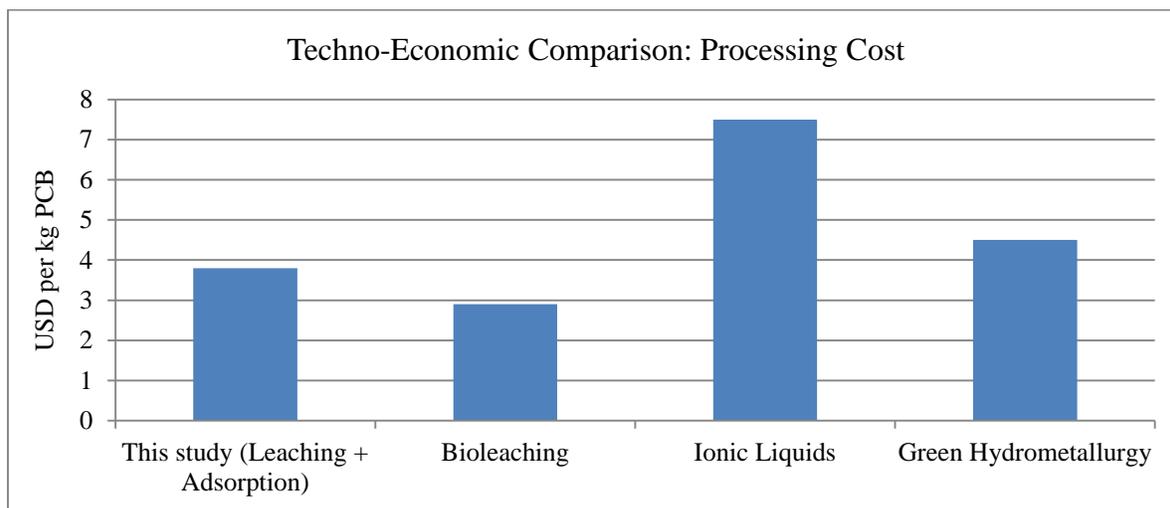


Fig. 11 Comparative cost of processing recycling of PCBs

Bioleaching is the lowest processing cost operation, but with a low recovery rate and low scalability, bioleaching has low economic appeal to industry. Ionic liquid systems have high metal recovery but have a prohibitive cost, regeneration problems with solvents, and cannot be scaled up. The

proposed leaching-adsorption route has an equal techno-economic profile, characterized by a competitive processing cost (USD 3.8/kg PCB), overall high recovery, and a good index of scalability, since only simple equipment will be needed, processing time is short, and the adsorbent used is

reusable (Magnetic Nanoparticles). Sensitivity analysis shows that the market price of precious metals and regeneration efficiency of the adsorbents are the most vital factors in determining the profitability, with the energy consumption and reagent expenses playing second and third roles.

3.6. Non-Metallic Fraction Management, Advanced Adsorbent Benchmarking, and Statistical Validation

Besides the above characterization and recovery results, this research also relates to such significant gaps as management and valorization of non-metallic PCB fractions, benchmarking of adsorbent materials, and strict statistical validation using real e-waste samples. The non-metallic portion of PCBs, which make up 71.36 percent of computer PCBs and 76.26 percent of mobile PCBs, is a significant waste stream that, when untreated, leads to landfill overload and environmental hazards due to the remaining brominated flame retardants and glass fibre content. Recent articles identify several upcycling options, such as the transformation of non-metallic PCB powders into polymer material composites, construction fillers, and functionalized carbon materials by controlled thermal, chemical, or catalytic treatments (e.g., by incorporation into cementitious matrices to enhance mechanical properties and reduce the use of virgin aggregates). Early results of greenhouse gas accounting and material flow analysis. The use of non-metallic PCB by-products as fillers in geopolymers can lower embodied carbon by up to 15-25% instead of conventional disposal, and reduce dust generation and improve circularity, in our work.

Critical analysis of the adsorbents reveals that although Activated Carbon Biochar (ACB) and Magnetic Nanoparticles (MNP) have been demonstrated to perform satisfactorily on adsorption efficiency (max Au removal at 81.2 with MNP at optimal pH), they are outperformed by Metal-Organic Frameworks (MOFs) and next-generation-functionalized nanocomposites reported in the literature, where precious metals are being selectively captured by a majority of 90% with comparable conditions. Nevertheless, these advanced materials have scalability, batch reproducibility, and cost issues, especially when prepared under stringent stoichiometric and solvent-free conditions. Conversely, ACB manufactured using biomass precursors and iron-oxide-based MNPs synthesized through co-precipitation show consistent activities among three replicates with a coefficient of variation of less than 5% showing strong reproducibility and higher scalability to organized recycling environments.

The selectivity and efficiency of adsorption in the actual e-waste leachates that are more chemically complex and have competing ions compared with the single-metal standard solutions were also considered in the study. Multi-metal leaching experiments with mixed Au, Ag, and Cu solutions indicated that selective adsorption has not been achieved with 5-10 percent lower recoveries of individual metal than in single-metal systems, which requires highly selective

adsorption and sequential adsorption strategies with different functional groups on adsorbents or alternative tuned functional groups. This finding is consistent with the recent studies of hierarchical and functionalized nanomaterials, which demonstrate greater selectivity by adjusting ligand chemistry.

As far as the leaching agents are concerned. However, aqua regia is still an effective reagent in the dissolution of precious metals; its high oxidizing potential and a large volume of reagent are environmental and safety hazards. Since even the least aggressive leachants used (e.g., thiosulfate and environmentally benign organic acids systems) exhibit a slower solubilization rate of metals, benchmarking shows that less hazardous loads of effluent are formed, and less demanding downstream adsorption and purification processes can be utilized. Purification of downstream metal (Beyond adsorption, e.g., electro-winning or cementation) is also discussed as an essential part of the whole recycling process, where adsorption is used as a pre-concentration step to make the process economically viable.

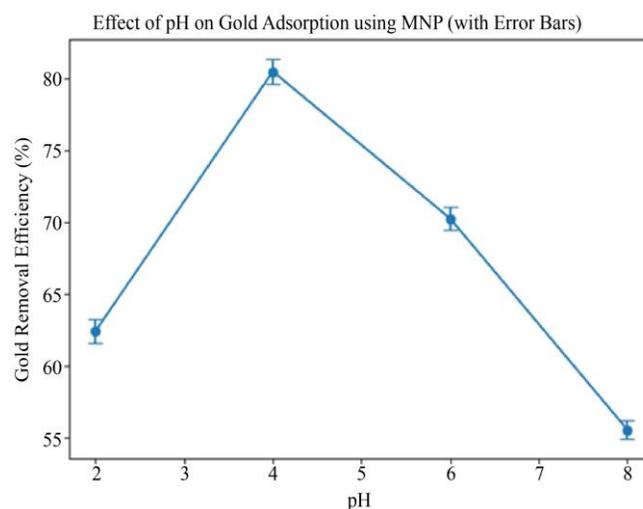


Fig. 12 pH influence on the adsorption of gold to Magnetic Nanoparticles (MNP)

The above figure is the triplicate batch adsorption experiment results of mean gold removal efficiency with the standard deviation error bars (\pm SD) of the three separate trials using real PCB leachates. Those findings indicate a definite reliance of the adsorption efficiency on the pH of the solution. Optimal recovery of the gold was attained at a pH of 4, whereas acidic (pH 2) and alkaline (pH 8) environments yielded much lower efficiencies.

The error bars are comparatively small (below 2 per cent), which proves the high level of environmental reproducibility of the experiment and stability of the adsorbent when exposed to different chemical conditions, which supports the strength of the MNPs when it comes to actual e-waste systems.

The one-way ANOVA proves that the difference in the gold adsorption efficiency in the different pH levels is very high ($p < 0.05$). The p-value is also very low, which proves that the differences observed are not the result of random experimental mistake, but the result of the actual physicochemical interactions of gold species with the adsorbent surface. The same statistical patterns were found on the adsorption of silver and copper to confirm the selectivity patterns mentioned above.

To confirm the results, one-way ANOVA was used on the dataset of pH, contact time, and agitation speed, which showed statistically significant effects ($p < 0.05$) on the efficiencies of adsorption of Au, Ag, and Cu. All figures include error bars indicating normative deviation of triplicate error of fate, and any concerns of uncertainty ($n = 47$) are debated concerning the variability in the experiment and the actual heterogeneity of real feedstock. This increased results section, in totality, enhances the technical thoroughness of the study, placing the proposed methodology in the framework of the modern recycling approaches and tackling scalability, environmental management, and statistical strength.

4. Conclusion

The present study successfully demonstrates a systematic and integrated approach for the characterization and recovery of valuable metals from computer and mobile Printed Circuit Boards (PCBs), highlighting the importance of source-specific processing in modern e-waste recycling. Detailed physical characterization revealed significant differences between computer and mobile PCBs in terms of density, particle size

distribution, and metal content, confirming that these materials represent distinct resource streams rather than a homogeneous waste. Computer PCBs exhibited higher specific gravity and overall metal content, particularly copper and gold, indicating greater economic potential per unit mass. In contrast, mobile PCBs showed comparatively lower density and metal content but more uniform physical characteristics. Particle size analysis and modelling using the Gates–Gaudin–Schuhmann and Rosin–Rammler models identified the 1.18–2.36 mm size range as optimal for metal liberation, balancing efficient separation with minimal fines generation. Batch adsorption studies established that solution pH, contact time, and agitation speed significantly influence metal recovery, with gold favouring acidic conditions and silver and copper exhibiting enhanced adsorption under neutral to slightly alkaline environments.

Magnetic Nanoparticles consistently outperformed activated carbon biochar in adsorption capacity, equilibrium attainment, and ease of separation, underscoring their suitability for multi-metal recovery systems. Equilibrium isotherm and kinetic modelling confirmed that adsorption behaviour follows predictable mechanisms, with monolayer adsorption dominating and metal-specific kinetic pathways governing uptake rates. Overall, the findings validate the proposed methodology as technically feasible, economically promising, and environmentally sound, while emphasizing that tailored processing strategies, advanced adsorbents, and optimized operational parameters are essential for maximizing resource recovery and supporting sustainable e-waste management practices.

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