Kinetic analysis of selective copper and zinc leaching from printed circuit boards

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The rapid growth of the electronics industry has resulted in a considerable increase in electronic waste (e-waste), with printed circuit boards (PCBs) representing a significant portion of this waste stream (Li et al., 2018). PCBs contain a complex matrix of metals, polymers, and ceramics, making their recycling both a challenge and an opportunity. Among the valuable metals embedded in PCBs, copper (Cu) and zinc (Zn) stand out due to their industrial relevance and economic value. Traditional disposal methods, such as landfilling and incineration, pose serious environmental risks due to the release of toxic substances and the loss of valuable resources (Xiu and Zhang, 2009; Menad *et al*, 1998). Therefore, developing efficient and sustainable metal recovery processes is essential for mitigating environmental pollution and promoting resource conservation.

Conventional recovery techniques, such as pyrometallurgical and biometallurgical methods, often suffer from high energy consumption, hazardous emissions, and non-selective metal dissolution (Rao *et al*, 2021). As a result, selective leaching has emerged as a promising approach to enhance metal recovery while reducing environmental impact. This process involves the dissolution of target metals under controlled conditions, allowing for the selective extraction of Cu and Zn from PCBs. The kinetics of this leaching process play a critical role in optimizing efficiency and maximizing recovery yields. In this study, we present a comprehensive kinetic analysis of the selective leaching of Cu and Zn from PCBs. According to a previous study (Rahimi *et al*, 2024), the leaching process is designed to be performed in two stages: the first targeting base metals and the second focusing on precious metals. This work was focused on the first stage. By employing controlled experimental conditions and mathematical modelling, we evaluate the reaction kinetics and mass transfer mechanisms.

A series of batch leaching experiments were conducted to investigate the effects of temperature and contact time (kinetics) on metal recovery (mg of metal/g of PCB). Nitric acid (HNO_3) was employed as the leaching agent with an optimal concentration of 3.4 M (Rahimi *et al*, 2024), 30 g/L solid/liquid ratio as an insignificant variable (Rahimi *et al*, 2024) and different temperatures of 30, 40 and 50°C for 6 h. Before leaching process, waste PCBs used in this research were pre-treated as explained comprehensively in our previous work (Rahimi *et al*, 2024). In summary, first, large electronic and non-electronic components (such as capacitors, resistors, IC chips, slots and connectors) were removed to separate valuable and hazardous parts. Subsequently, the solder mask (epoxy coating) covered on the surface of PCBs was eliminated using diluted sodium hydroxide solution (2% w/v) under autoclaving condition. To reduce the size into smaller particles, the PCBs were then cut down followed by crushing to increase the accessibility for leaching. The particles in the size range of 0.1-2 mm were used for the leaching experiments. The leaching kinetics was analyzed using classical kinetic models, including the first and second order equations. Activation energy (E_a) was also determined through the Arrhenius equation.

The data shown in Figure 1 provide insights into the dissolution behavior of Cu and Zn over time under varying thermal conditions. A sharp increase in Cu recovery is observed in the first 50 minutes at all temperatures (Figure 1A). This indicates fast dissolution of Cu from PCB materials, likely due to the availability of exposed copper particles and their reaction with the leaching agent. Beyond 100 minutes, the recovery rate slows as the process reaches equilibrium. The flattening of curves at longer contact times suggests a progressive depletion of easily leachable copper and possible diffusion limitations. Moreover, higher temperatures resulted in enhancing copper leaching performance, so that at 50°C, the equilibrium Cu recovery reached approximately 525 mg/g, compared to 475 mg/g at 40°C and 425 mg/g at 30°C. This suggests that increasing temperature accelerates copper dissolution by improving reaction kinetics and reducing mass transfer resistance. Zn exhibited a similar trend to Cu but reaches much lower recovery values (~40 mg/g at 50°C, ~35 mg/g at 40°C, and ~30 mg/g at 30°C), which could be related to its much lower initial content in PCBs (30.36 mg/g PCB compared to 450.08 mg/g PCB for Cu). The experimental data were best fitted to the first order model, and the fitting curves are presented in Figure 1. The apparent activation energy values for Cu and Zn dissolution were found to be 42.58 kJ/mol and 31.40 kJ/mol, respectively (Figure 2), indicating that Cu and Zn leaching is chemically controlled.

This work offers valuable insights into the development of economically viable metal recovery techniques from e-waste, aligning with global efforts toward circular economy initiatives and sustainable resource management. The proposed kinetic model serves as a foundation for industrial applications in recovering critical metals from discarded electronic components.

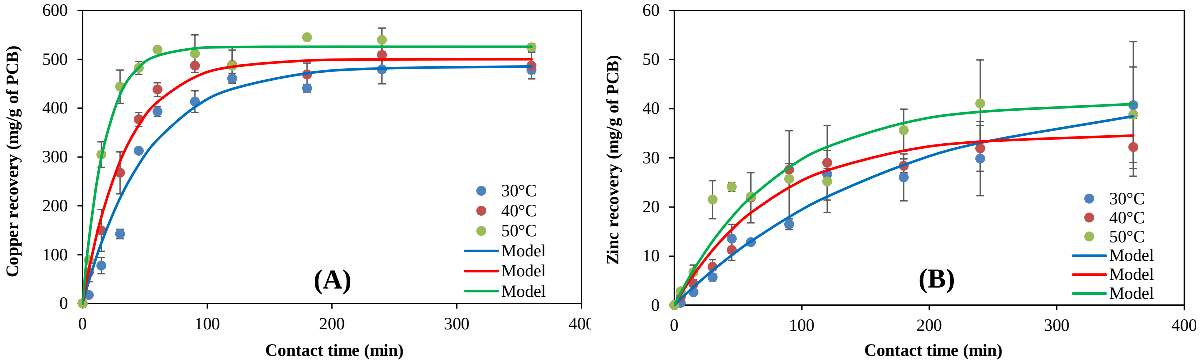

Figure 1. Leaching kinetics of A) Cu and B) Zn from PCBs at various temperatures. Solid lines correspond to the first order model

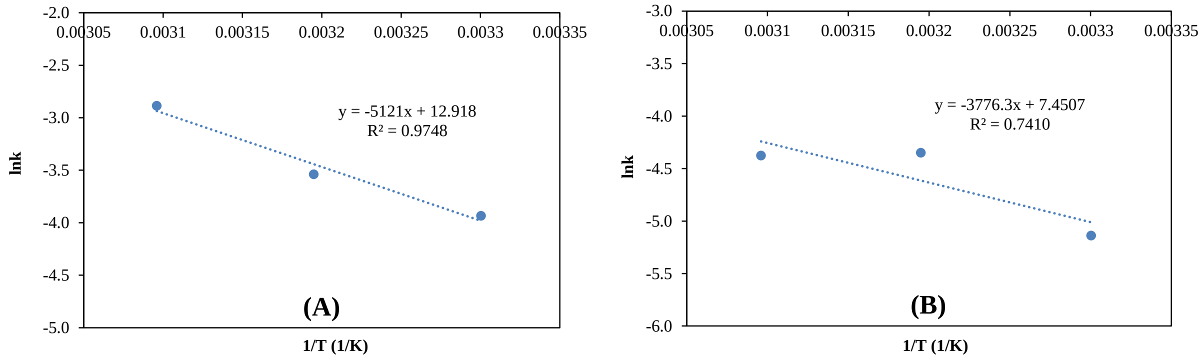

Figure 2. Arrhenius plots to determine activation energy for the leaching of A) Cu and B) Zn from PCBs

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