

Two-stage sustainable approach for tin recovery from waste PCBs using *Acidithiobacillus ferrooxidans* leaching and bentonite clay adsorption

Murugesan Manikkampatti Palanisamy^{1*}, Padmapriya Veerappan², Kalaivani Ramanathan², Nivedha Subramanian³, Srinithi Jeyachandran⁴, Senthilkumar Kandasamy⁵ & Sivakumar Palanisamy⁶

^{1*}Department of Petrochemical Technology, Excel Engineering College, Komarapalayam, Tamil Nadu-637303, India

²Department of Electronics and Communication Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu-638057, India

³Department of Chemical Engineering, Gnanamani College of Technology, Namakkal, Tamil Nadu-637018, India

⁴Department of Chemical Engineering, Kalasalingam Academy of Research and education, Krishnankoil, Tamil Nadu-626126, India

⁵Department of Food Technology, Kongu Engineering College, Perundurai, Erode, Tamil Nadu- 637303, India

⁶R&D Laboratory, Excel Engineering College, Komarapalayam, Tamil Nadu- 637303, India

*E-mail: enginermuruges@gmail.com

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Tin (Sn), a precious metal widely used for corrosion resistance applications in several industries, which was present 42.40 weight % in the unused printed circuit boards (PCBs). This waste globally affects the environment. Therefore, this research emphasizes on tin recovery by two stage operations like Leaching by *Acidithiobacillus ferrooxidans* and adsorption by Bentonite clay) with the help of RSM technique. This study has been achieved 97.33% tin recovery with a desirability rate of 0.845 under optimized parameters such as temperature 29°C, PCBs sample size 0.25 µm, pulp density 22.06 g/L and time 28 days. Optimized values applied the experimental bacterial leaching and achieved 97.7% of tin recovery efficiency and optimized parameters (leaching duration of 21 days, a pulp density of 15 g/L, a particle size of 0.25 µm and a temperature of 20°C). After bacterial leaching, study is continued adsorption with clay (Bent) for reclaiming the tin (Sn²⁺) from bio-leachate solution which was recovered 97.86% under optimized parameters (temperature - 80°C, Adsorbent dosage - 4 g, Bent size - 0.05 mm and time - 4 h). However, choosing this toxic free bacterial leaching and bent clay adsorption techniques could promote tin recycle without affecting the environment.

Keywords: *Acidithiobacillus ferrooxidans*, Bentonite clay, RSM, Tin recovery, Waste PCBs

Introduction

Tin is a precious industrial metal known for its ability to alloy with others, enhancing surface properties in electronics, soldering, and foodgrade container coatings^{1,2}. Particularly, tin constitutes 42.4% of metal content in e-waste³. The Global E-Waste Monitor 2024 reports a sharp rise in global e-waste, from 66.3 million tonnes in 2024 to a projected 82 million tonnes by 2030, driven by rapid tech growth and shorter device lifespan. However, formal recycling remains low rising only from 15% in 2014 to 26% in 2024, and expected to reach 30% by 2030⁴ (Fig. 1). This emphasizes the urgent need for sustainable strategies to reduce environmental impacts and recover valuable metals like tin. E-waste contains hazardous metals (Pb, Mg, Cu, Al, Fe) mixed with polymers and ceramics^{5,6}, which, when dumped in landfills, pollute soil, water, and air⁷, causing health risks including organ damage and neurological

disorders^{8,9}. This study addresses environmental challenges by recovering tin from printed circuit boards (PCBs) using two green technologies leaching and adsorption selected to minimize environmental harm observed in conventional recovery methods.

Tin recovery from waste PCBs is important due to its industrial value and environmental implications. Various methods have been developed for tin metal extraction, each presenting unique challenges. Pyrometallurgical methods, while efficient, consume high energy and emit hazardous pollutants like dioxins and heavy metals, causing soil and air contamination¹⁰. Hydrometallurgical techniques employ chemicals such as acids and cyanide, which pose severe environmental and health hazards including water pollution, respiratory illness, and skin or kidney damage¹¹. Mechanical separation methods like crushing and electrostatic separation are faster but less efficient, often leading to material loss and excess solid waste¹². Biohydrometallurgy, using

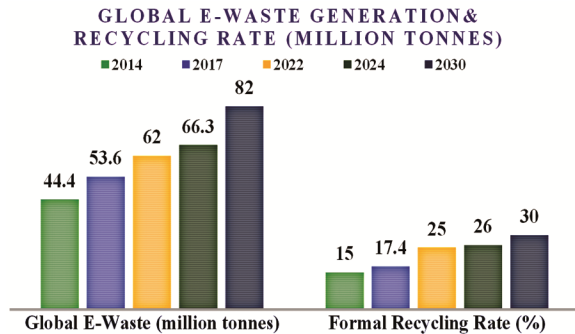


Fig. 1 — Global E-wastes generation and recycling rate per year wise

microorganisms, is more eco - friendly but remains slow and commercially less viable for tin recovery¹³. Chemical leaching, although effective, involves toxic reagents that pose serious health risks and pollute ecosystems¹⁴. A promising alternative is bacterial leaching using *Acidithiobacillus ferrooxidans*, which can oxidize tin into soluble forms, enabling recovery from industrial effluents and contaminated waters^{8,15-18}. However, reclaiming tin from bio-leachate using conventional methods like electro-winning still faces chemical and operational drawbacks. Thus, the inefficiencies and environmental burdens of existing recovery methods underscore the need for a cleaner, efficient, and scalable solution for tin reclamation from PCBs.

Based on existing literature, bentonite clay is emerging as a cost-effective, eco-friendly adsorbent for tin recovery from leachates due to its high surface area, strong cation exchange capacity, and metal-binding affinity¹⁹. Different modification techniques, including acid activation and surface functionalisation, have been shown to significantly improve its adsorption efficiency²⁰. Factors like pH, temperature, initial tin concentration, and contact time play important roles in improving its adsorption efficiency^{21,22}. Recent research has shown bentonite clay's effectiveness in removing tin from aqueous media, offering a sustainable alternative to toxic recovery methods. Therefore, the current study proposes a two-stage eco-sustainable approach combining bioleaching using *Acidithiobacillus ferrooxidans* with adsorption by bentonite clay to recover tin from waste PCBs. This dual method not only reduces reliance on harmful chemicals but also supports circular economy practices in electronic waste management. The study aims to: (i) optimize the bioleaching process for efficient tin solubilization; (ii) apply bentonite clay for recovering tin from the leachate; (iii) optimize key adsorption parameters such as dosage,

particle size, temperature, and contact time using RSM; and (iv) establish a green, scalable model for tin recovery with minimal environmental impact. This approach supports sustainable recycling while mitigating health and ecological hazards linked to conventional processes.

Experimental Section

PCBs collection and preparation of sample

A total of 1000 g of unusable waste PCBs were collected from an e-waste disposal facility located in Salem district, Tamil Nadu. Sample collected PCBs were manually cleaned using an air blower to remove dust. The primary manual separation process was used for disassembly, where components such as capacitors, resistors, integrated circuits, diodes, and transistors by using various mechanical tools, including hacksaws, tin snips, sheet metal cutters, cutting pliers, and demolition toolkits. This manual separation followed by processing for particle size reduction through unit operations. The PCBs were disassembled, heated in a muffle furnace at 700 - 900°C to enhance durability and crushability, and subsequently crushed using a jaw crusher. Adjusting the jaw crusher clearance from 10 mm to 5 mm significantly improved the size reduction of sample. After that, crushed PCBs were pulverized and milled in a ball mill to achieve various particle sizes, followed by sieving with a rotary sieve shaker at 60 rpm. The different mesh sizes were used to separate particles and recovered 0.25 μm sizes of powdered sample.

Bacterial leaching variables optimization by RSM

The effect of various independent variables on the response were investigated using RSM. In this study, the Three-level Design (TLD) was employed to design bleaching tests. The design utilized three levels, represented by coded values of -1 (low), 0 (center), and (1) high values. The actual values were determined using Eq. (1), and the relationship between actual and coded values was established through Eq. (2). Eq. (3) was utilized for the determination of experiment counts (N) in a Three-level design. Consequently, 17 trials were required for three parameters ($n = 3$) setup with three repeated measurements ($cp = 3$) at the middle point. Second-degree models, as described in Eq. (4), were founded to ascertain the response (Y) as derived from the experimental results, as detailed in study²⁵.

$$X_{Centre} = \left(\frac{X_{centre} - X_{low}}{2} \right) \quad \dots (1)$$

$$X_{Coded} = \left(\frac{X_{actual} - X_{centre}}{X_{centre} - X_{min}} \right) \quad \dots (2)$$

$$N = n^2 + n + c_p \quad \dots (3)$$

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad \dots (4)$$

Where, X_{actual} , X_{centre} , and X_{min} correspond to the true value, the center value, and the smallest (low) true value, correspondingly, with X_{coded} representing the coded value. In this study, we denote the number of variables as 'n' and the repeats in the middle point as 'cp.' Furthermore, ' γ ' represents the expected outcome, ' β ' denotes the coefficient, ' β_1 ', ' β_2 ', ' β_3 ', and ' β_4 ' stand for the linear coefficients, while ' β_{12} ', ' β_{13} ', ' β_{23} ', ' β_{11} ', ' β_{22} ', and ' β_{33} ' represent the interaction constant and quadratic coefficients. The symbols ' X_1 ', ' X_2 ', ' X_3 ', and ' X_4 ' are used to represent the predictor variables. The primary aim of this study is to examine the impact of these parameters on bioleaching processes.

Optimization of operating variables with RSM using DOE

The current study involved simulating and analyzing multiple parameters to determine the optimal values for key factors (A: Time in days, B: Temperature in °C, and C: Pulp density in g/L), as indicated in Table 1. The extraction of Sn^{2+} metal ions from PCBs was attained through RSM. Preliminary experiments demonstrated that time, temperature, and pulp density are the primary factors influencing the process.

The benefits of RSM were applied to analyze the leaching process across a wide range of variable parameters while minimizing the number of required experiments. To enhance the tin recovery rate, the independent process variables were optimized and analyzed, taking into account the operational parameters, with a goal to minimize the number of experiments. The leaching of tin, was done by Central Composite Design (CCD) and RSM was done for maximizing tin recovery. The outcome of the CCD

experimental analysis was done, both experimental and predicted values of tin recovery. The DOE was analysed as optimized parameters (temperature - 20°C, PCBs sample size - 0.25 μm , pulp density - 20 g/L and time - 21 days) for *Acidithiobacillus ferrooxidans* (Bacterial Leaching). These optimized parameters were used for bacterial leaching then results were compared with predicted results.

Bioleaching experiments using bacterial leaching for tin recovery

Bioleaching experiments using *Acidithiobacillus ferrooxidans* bacteria were conducted to recover the Sn^{2+} from powdered PCBs sample. In these operations nutrient broth solution typically used a s9K medium, specifically designed to support the growth and activity of this bacterial species. The composition of the 9K medium includes with peptone (5 g/L) as a nitrogen source, beef extract (3 g/L) for vitamins and growth factors, and sodium chloride (5 g/L) for osmotic balance, facilitated bacterial growth. The broth was prepared in distilled water, adjusted to pH 7.0, and sterilized at 121°C for 15 - 20 min before use. PCB samples were introduced into the broth, and the bioleaching experiments were conducted by varying parameters such as temperature (20 - 30°C), pulp density (5 - 25 g/L), and leaching durations (7, 14, 21, and 28 days). Other parameters, such as the initial particle size of <0.42 mm, were kept constant to ensure consistent conditions. The prepared samples were enclosed in conical flasks with *Acidithiobacillus ferrooxidans* bacteria. Also, morphological and elemental changes during the leaching process were monitored using EDX analysis. The results reported that optimal leaching conditions were achieved Sn^{2+} , 96.6% at a temperature of 20°C, a grain size of 0.25 μm , a pulp density of 20 g/L and 21 days. These results underscore the 96.6% efficiency of bacterial leaching, offering a sustainable alternative for tin recovery from e-waste. The tin leaching efficiency was calculated by Eq. 5.

$$\text{Leaching efficiency (\%)} = (C_0 - C_e) / C_0 \times 100 \quad \dots (5)$$

Table 1 — Levels of various process variables in both coded and uncoded forms, focusing biological leaching using the Box-Behnken method

Variable	Name of the process variable	Range and levels		
		Bio-Leaching		
		-1	0	1
A	Time (h)	14	21	28
B	Temperature (°C)	24	28	32
C	Pulp density (g/L)	15	20	25

The initial amount of tin in PCB sample is denoted by C_o , and C_e represents the after completion (after attain the equilibrium) of bioleaching in tin presence. It was evaluated by the weight % of tin presence in initial and after leaching with the help of EDXs analysis. The results are shown in Fig. 3.

Reclamation of tin from leachate solutions using adsorption

Tin reclamation is most important process for tin recovery. Previous studies involved the recovery of tin by sedimentation, electroplating processes, electrowinning and electrochemical process but these methods have their own limitations for environmental soil, water and air pollution. Therefore, need to develop a new technique for effectively separating Sn^{2+} from leached solutions. Based on previous studies¹⁹⁻²² effectively reported green way of adsorption techniques by bent adsorbent for recovering tin. In these operations adsorbent need to activate for enhancing the surface area of the adsorbent with the help of thermal activation method. Hence, previous studies^{25,28} was conducted optimization investigations to maximize the recovery of heavy metal ions from diverse solutions. However, none of these prior studies have focused on optimizing parameters using Bentonite in leached solutions derived from PCBs. Therefore, the primary objective of our study is to determine the optimal conditions for achieving an enhanced recovery rate.

Bent adsorbent activation by thermal method

The activation of the bent adsorbent involves thermal activation for increase the adsorbent surface area. Initially, thermal activation, achieved by heating 250 g of clay were taken in a thermal crucible and maintain the 900°C temperature at five hours. As a result, the obtained samples have particle sizes ranging from 1 μm to 5 μm . This process increases the specific surface area by removing undesirable vapours from the Non-Reactive Adsorbents (NRA). The T-A Bent sorbents were enhanced surface area with particle size 5 μm and surface morphology is depicted in Fig. 4.

Adsorption of tin ions onto bentonite and characterization via SEM with EDX analysis

The input for the sorption process consists of a Leachate obtained through bacterial leaching. In this reclamation operations were performed under thermally activated Bent using a batch system. Based on previous studies sorption methodology was conducted at optimal parameter ranges, including a

temperature of 80°C, a sample size of 0.5 μm , adsorbent dosage 4 g, concentration of leachate 20 mL (volume) and a duration of 4 h. The mixture was shaken at the shaking speed of 200 rpm for 4 h at 80°C. Upon completing the tin reclaim from leachate, filtration process was done with the help of Whatman filter paper. After that, tin concentration was examined using EDXs, which is utilized for elemental characterization testing in conjunction with SEM with EDXs images. PCBs Size reduction & Primary analysis – (a) PCBs sample, (b) Thermal treatment with crushed PCBs sample, (c) Heavy metals present by SEM image, (d) Metal composition by EDX Spectrum are shown in Fig. 2. The EDX analysis typically utilizes a beam current with an energy range of 100 nA, a Schottky emitter operating between -200 V and 30 kV, magnification levels from 12X to 105X, and a resolution of 2 nm, achieved using gold nanoparticles deposited on a carbon support. The thermally activated Bentonite exhibited a particle size of 0.5 μm . These findings were confirmed through SEM images, which demonstrated the morphological characteristics and size distribution of the adsorbent materials.

Subsequently, the efficiency of the adsorption of bent adsorbents was determined by Eq. 6.

$$\text{Removal efficiency (\%)} = (C_o - C_e) / C_o \times 100 \dots (6)$$

Where: C_o is the original concentration of Sn^{2+} from leachate (BL) samples. C_e is the final concentration of Sn^{2+} remaining in solution after the adsorption process²³⁻²⁵. The overall process was shown in Fig. 3.

Results and Discussions

Presence of tin from powdered sample by EDXs analysis

The size reduction and size analysis process was performed with the help of SEM (Scanning Electron Microscopy) analysis and the images are shown in Figs 2 and 4. The analysis was done based on previous study^{26,27}, while size reduction significantly increased the surface area, enhancing the tin recovery efficiency. SEM analysis showed the primary structure of the size-reduced sample (0.25 μm), showing granular, spherical PCB particles with a rough surface. The prepared 0.25 μm samples were analyzed for morphology and metallic elements using SEM with EDX (SEM-FEI-Quanta FEG 200F). The beam current typically ranged from 100 nA, with a Schottky emitter varying between -200V and 30kV,

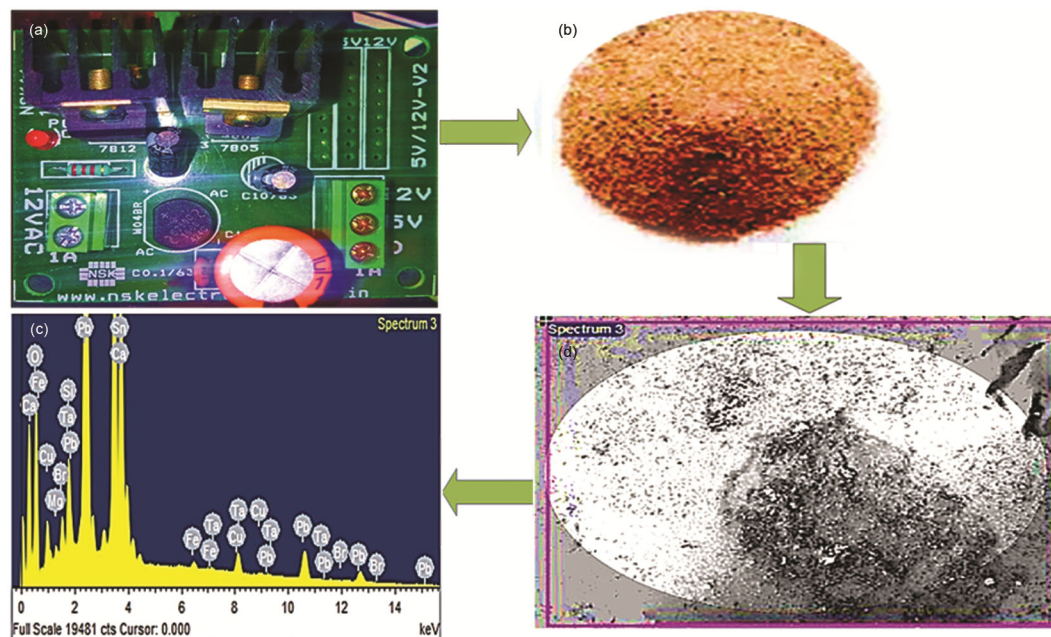


Fig. 2 — (a) PCBs sample, (b) thermal treatment with crushed PCBs sample, (c) heavy metals present by SEM image and (d) metal composition by EDX spectrum

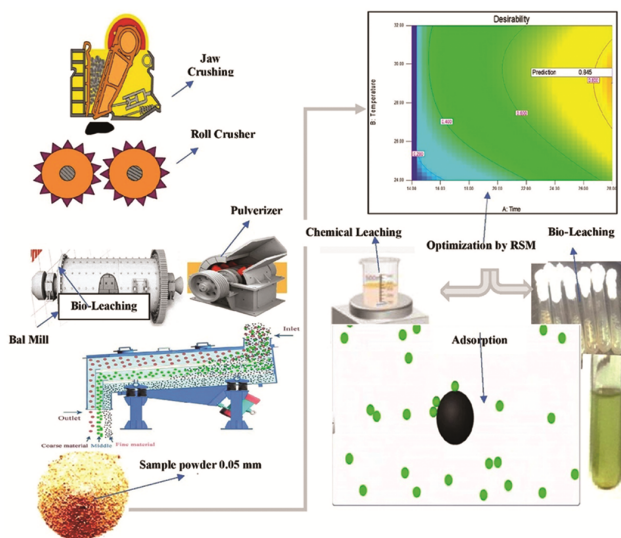


Fig. 3 — Overall process of tin recovery by two stage operations

magnifications from 12X to 105X, and a resolving power of 2 nm (Gold Nano-crystals on a carbon support). This analysis trusts on the unique atomic structure of tin, resulting in distinctive peaks on the electromagnetic emission spectrum due to different electron transitions²⁴. EDX analysis identified strong spectrum peak of tin and other metals like Cu, Zn, Pb, Fe, Ti, Ca, and Br. The results indicated metal percentages, with Sn at 42.40%, Cu at 3.15%, Pb at 27.81%, Zn at 1.16%, and other metals at 25.48%.

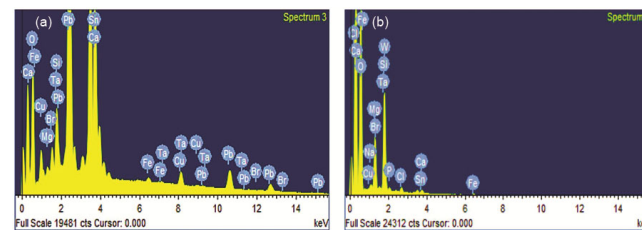


Fig. 4 —EDX spectra of the adsorbent (a) before and (b) after bacterial leaching treatment

Optimization by Design of Experiments (DOE)

Table 1 presents the selected variables and their corresponding levels used in the *Acidithiobacillus ferrooxidans* bacterial leaching experiments. The experimental results were statistically analyzed using Design Expert 8.0.6 software, which involved a detailed comparison of predicted and actual values through a CCD. The analysis included ANOVA (Analysis of Variance), desirability functions, response surface plots, and the interaction effects of temperature, pulp density, and time duration to optimize the leaching of tin from PCBs sample²⁸. The Three-Dimensional contour plots visualize two scenarios: one where certain factor is held constant while the others vary. The statistical analysis involved regression analysis techniques that yielded quantitative data based on the design of experiments. The stimulated and actual design values for CCD are presented in Table 2. The parametric Eqs. (1-4) were specified to analyse

Table 2 — Experimental and predicted design values of bioleaching from CCD

Run No	A	B	C	A	B	C	Biological Leaching	
							Experimental	Predicted
							Sn	Sn
1	-1	0	-1	0	0	0	92.57	94.47
2	-1	0	1	-1	0	1	96.11	96.79
3	1	0	-1	0	-1	1	95.67	94.98
4	1	0	1	1	-1	0	95.18	96.78
5	0	-1	-1	1	0	-1	95.04	94.95
6	0	-1	1	0	1	1	95.64	94.25
7	0	1	-1	0	1	-1	91.98	91.95
8	0	1	1	0	0	0	97.01	96.78
9	-1	-1	0	0	0	0	94.61	97.15
10	1	-1	0	-1	0	-1	91.25	91.39
11	-1	1	0	0	0	0	89.86	90.90
12	1	1	0	1	1	0	97.51	97.15
13	0	0	0	0	-1	-1	95.27	95.97
14	0	0	0	-1	-1	0	95.48	95.72
15	0	0	0	-1	1	0	97.65	97.11
16	0	0	0	1	0	1	97.7	97.52
17	0	0	0	0	0	0	97.62	97.03

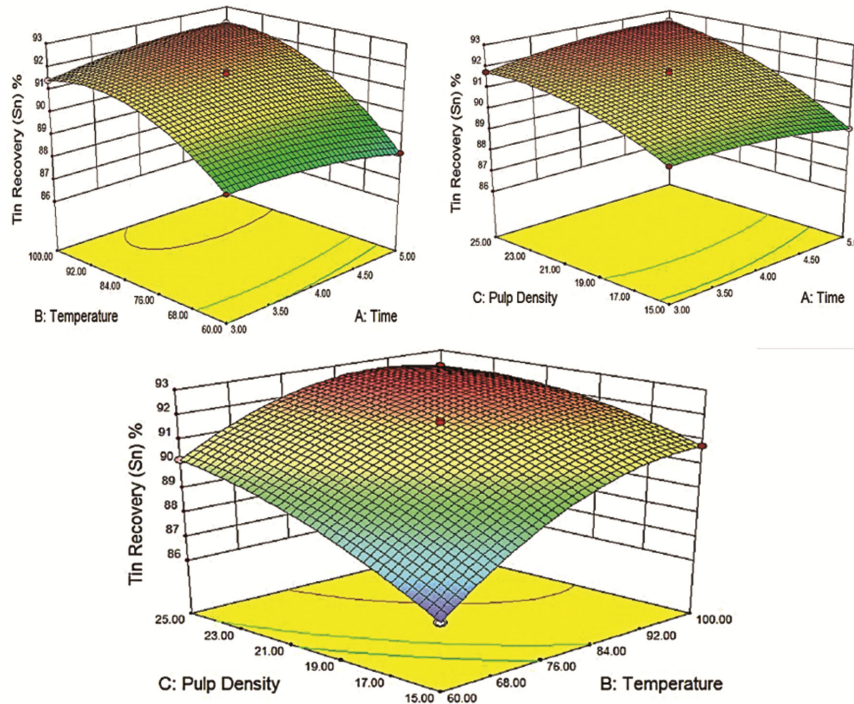


Fig 5 — Surface plots showed predicted results in tin recovery with interaction between temperature, time, and pulp density

visual representation of tin recovery from PCBs using statistical analysis.

The analysis was done for Regression Equation, Surface Plots, and Regression equation in Terms of processed variables for tin Separation from PCBs. Surface plots showed predicted results in tin recovery with interaction between

temperature, time, and pulp density are shown in Fig. 5. The coded equation plays a crucial role in assessing and comparing the impacts of different parameters by examining the coefficients of these factors, as demonstrated by the authors^{29,30} in their 2018 study. Consequently, the final regression equation (Eqs. 10 & 11) provides a representation in

terms of the actual factors (Eq. 7) involved in *Acidithiobacillus ferrooxidans* bacterial leaching processes of tin. This equation allows us to understand and quantify the influence of each factor on the recovery of tin from sample, thereby aiding in the optimization of leaching operation. The regression equation in coded factor (7) in tin recovery with actual factor Eq. (8)

$$\text{Sn (Bio - Leaching)} = +96.02 + 1.09 \times A + 0.81 \times B - 0.022 \times C - 1.01 \times A \times B + 1.11 \times A \times C + 2.75 \times B \times C + 0.24 \times A^2 - 1.37 \times B^2 - 1.34 \times C^2 \quad \dots(7)$$

$$\text{Sn (Bio - Leaching)} = +69.86950 + 0.32629 \times \text{Time} + 3.00963 \times \text{Temperature} - 2.38210 \times \text{Pulp density} - 0.035982 \times \text{Time} \times \text{Temperature} + 0.031643 \times \text{Time} \times \text{Pulp density} - 0.013763 \times \text{Temperature} \times \text{Pulp density} + 4.814814E - 003 \times \text{Time}^2 - 0.085797 \times \text{Temperature}^2 - 0.053510 \times \text{Pulp density}^2 \quad \dots(8)$$

Assessment of Model Variance Using ANOVA (Analysis of Variance)

The analysis was employed to evaluate the stability of the models. The validation process was carried out using analysis of variance (ANOVA) based on the experimental data shown in Table 2. The low p-value (<0.05)-0.0077 and F-value 7.33961 (*Acidithio bacillus ferrooxidans*) bacterial leaching for Sn demonstrate the model's accuracy. Additionally, the acceptable lack of fit with F-values of 0.74698 bacterial leaching (BL), along with p-values greater than 0.05 (showed p-values -0.5780), indicate that the method effectively represents the

experimental data. The ANOVA table was developed to predict the recovery of tin (Sn²⁺) using bacterial leaching treatments. This model was created using experimental data concerning parameters such as contact time (A), temperature (B), and sample pulp density (C), as shown in Table 3. The high R² values of 0.9042 (BL) indicate a strong correlation between the experimental and predicted outcomes. Moreover, the predicted R² values of 0.7810 (BL) show reasonable consistency with the adjusted R² values. The model's reliability in exploring the design space is further supported by its adequate precision, demonstrated 97.33% (BL).

Experimental and Predicted Data Comparison with Desirability Optimization for Tin Recovery

The comparison plot between experimental and predicted data (Fig. 6), demonstrates that the predicted response values from the model closely

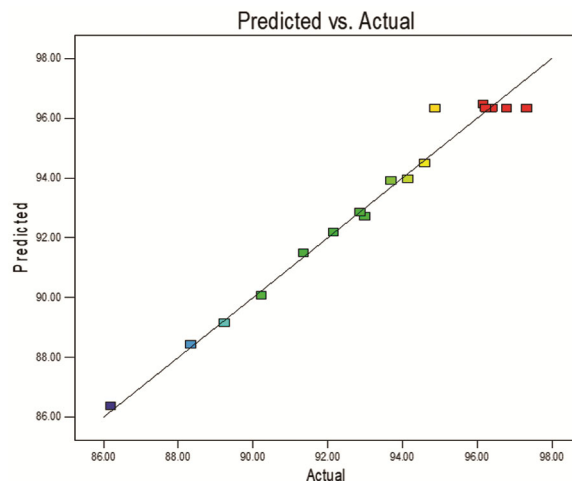


Fig. 6 — Comparison plot between the actual and predicted data correlations for bacterial leaching

Table 3 — Model analysis for predicting the percentage of tin in bacterial leaching

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F
Model	70.2702	9	7.8078	7.33961	0.0077
A-Time	9.4178	1	9.4178	8.85306	0.0206
B-Temp	5.21645	1	5.2164	4.90364	0.0624
C-Pulp den.	0.00405	1	0.0040	0.00380	0.9525
AB	4.06022	1	4.0602	3.81675	0.0917
AC	4.90622	1	4.9062	4.61202	0.0689
BC	30.3050	1	30.305	28.4877	0.0011
A ²	0.237	1	0.237	0.22278	0.6513
B ²	7.93449	1	7.9344	7.45870	0.0293
C ²	7.53505	1	7.5350	7.08321	0.0324
Residual	7.44653	7	1.0637	-	-
Lack of Fit	2.67385	3	0.8912	0.74698	0.5780
Pure Error	4.77268	4	1.1931	-	-
Cor Total	77.7168	16	-	-	-

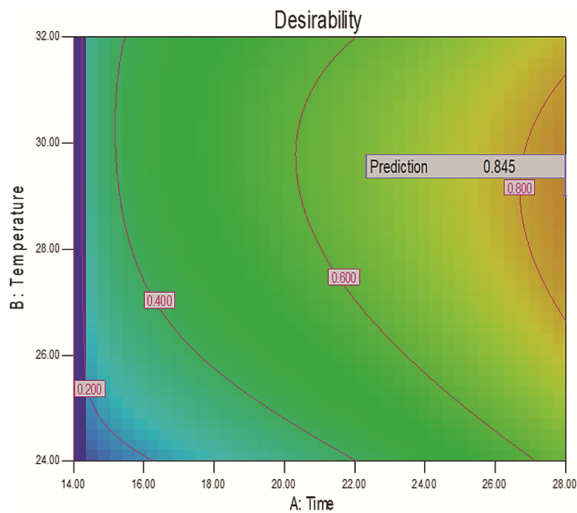


Fig. 7 — Plot for desirability prediction rate 0.845 as experimental Bioleaching

align with observed values across the selected range of independent variables, exhibiting high coefficients of determination ($R^2 = 0.9042$) in bacterial leaching. The actual vs predicted values plot further confirms good agreement with an adjusted R^2 value of 0.9042. In this study, the objective was to maximize the percentage recovery of tin, achieving an optimal removal of 97.33% Sn with a desirability value of 0.845 under similar conditions.

The experimental and predicted tin separation values were analyzed in the biological leaching process, with desirability rates within the prediction range of 0.845. Fig. 7 provides the desirability profile for tin recovery%, ranging from 0.0 (undesirable) to 1.0 (highly desirable). Under bioleaching conditions, optimal tin removal of 97.33% was achieved with a desirability value of 0.845 at 28 days, a temperature of 29°C, and a pulp density of 22.06 g/L.

Experimental analysis for optimized variables

Experiments were conducted under above optimized values, as determined by the statistical approach, closely matched the predicted values from the RSM. During the study, various parameters were adjusted, with powdered PCB samples introduced into nutrient broth solutions for leaching trials. The initial stages involved testing with different pulp densities (0, 5, 10, 15, 20, and 25g/L), while other variables such as a 28-day leaching period, 0.25 μm particle size, and 20°C temperature were kept constant. Bacteria were inoculated, and the mixture was stirred on a magnetic stirrer, followed by separate incubation. The reduction in tin content was determined via EDX analysis. After 21 days, leaching reached saturation

due to the feed's tin ion (Sn^{2+}) saturation by pulp density. Consequently, the optimized results indicated a Sn^{2+} recovery rate of 95.83% within the 21-day timeframe. Subsequently, temperature optimization was carried out at different levels (20°C, 22°C, 24°C, 26°C, 28°C, and 30°C).

The experiment extended under the specific essential role of temperature in the bioleaching process for recovery of tin ions. It became clear that the maximum separation rate was found with the ranges between 20°C and 32°C temperature as indicated in Fig. 8, where the most significant progress was observed. However, as the temperature surpassed 20°C, the separation process initiated to slow, reducing the overall tin recovery rate. In the end, recovered 96.23% recovery of Sn^{2+} , with only a minor error deviation of 1.16%, achieved at the optimal temperature of 20°C. Initially, as time progressed, the leaching rate increased little by little until it reached its peak before gradually drop down. Leaching experiments were conducted at separate intervals like 7 days, 14 days, 21 days, and 28 days, while keeping other conditions constant a temperature of 20°C, 0.25 μm particle size, and a pulp density of 12 g/L. However, between days 7 and 14 of leaching, the recovery rate of tin (Sn^{2+}) reached at 89.7%. The most efficient leaching occurred between 14 and 21 days, with a maximum leaching efficiency of 96.31% for Sn^{2+} it shown in Fig. 9. Towards the end of 28 days, there was a decrease in the removal rate, leading to the inference that 21 days represented the optimum leaching time.

In result, the optimal conditions for recovering tin ions were identified as a sample size of 0.25 μm particle size, a leaching duration of 21 days, a pulp density of 15 g/L, and a temperature of 20°C, resulting in a maximum recovery rate of 97.7% for Sn ions. These parameters represent the highest removal efficiency achievable under the specified optimal conditions, as evidenced by the EDX analysis. The results confirm the effectiveness of bioleaching in reducing metal content in PCBs, offering an eco-friendly and manageable approach. Notably, the bacterial leaching performed higher recovery efficiency (97.7%).

Investigation and operating parameters optimization for tin reclaim by adsorption

This research involved recovering tin from bacterial leached solutions by using Bent adsorbent with thermally activated. In this separation involved operating parameters finalizing which is minimize the operating cost, time consumption and quality &

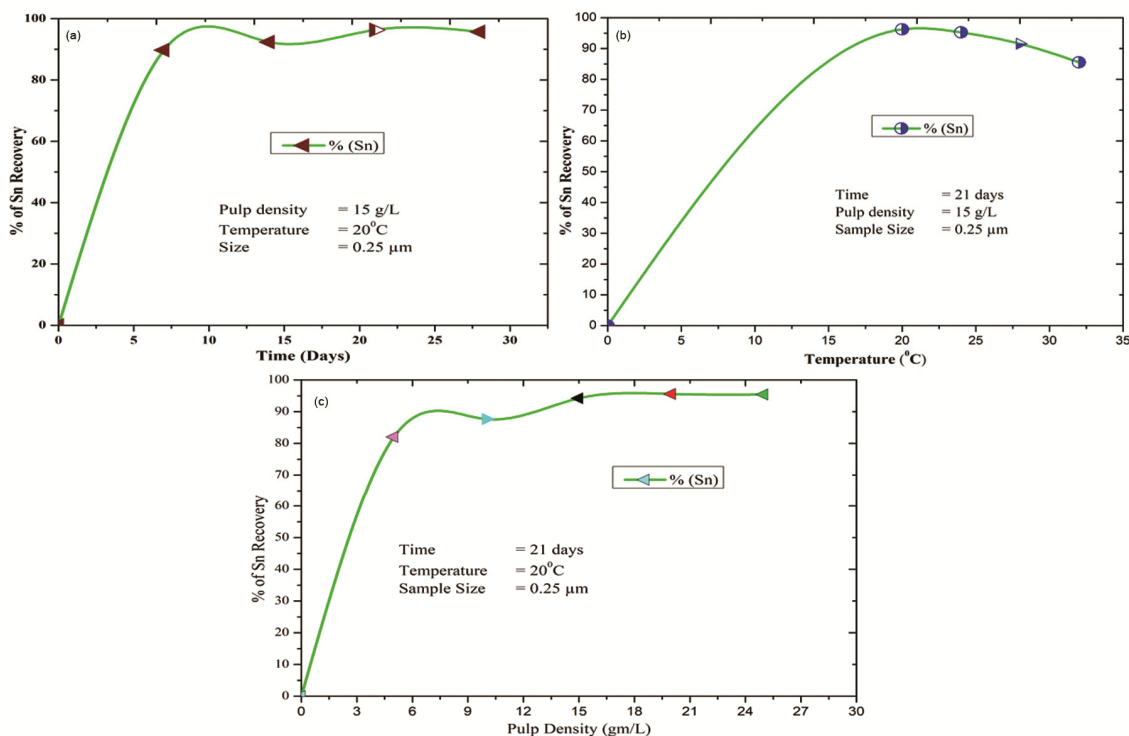


Fig. 8 — Graphical representations for effects for (a) Time, (b) Temperature and (c) Pulp density for recovery of Sn^{2+} by bacterial leaching

quantity of tin recovery. Therefore, process variables including adsorbent dosage (ranging from 0 to 10 g), concentration under volume (ranging from 0 to 40 mL), adsorbent particle sizes (ranging from 10 mm to $0.05 \mu\text{m}$), contact time (ranging from 0 to 4 h), and temperature (ranging from 40 to 120°C). Consequently, the optimized values derived from the experimental results.

Effect of contact time

Contact time significantly impacts the adsorption efficiency. Under consistent conditions of 5 g adsorbent, $0.05 \mu\text{m}$ particle size, shaken in 20 mL of leached solution at 200 rpm, 80°C temperature and adsorption occurred for 1 to 5 h. Results during the 1 to 4 h period showed thermally activated (T-A) bent were achieved Sn adsorption efficiency of 89% to 96%. Subsequent analysis revealed a gradual rise in adsorption rate from 1 to 3 h, followed by linear equilibrium. Optimal metal ion removal occurred between 2 to 4 h, indicating higher efficiency for Sn^{2+} ion adsorption during this timeframe. Subsequent experiments employed a 4 h contact time, resulting in a maximum tin recovery of 96% at the 3 h mark.

Effect of Adsorbent dosage

Experiments were conducted with varying leached solution to adsorbent ratios like 20 mL of leached

solution is constant for all stages with linearly increased the adsorbent dosage in grams like 20:2, 20:4, 20:6, 20:8, and 20:10. The adsorption rate increased linearly with the dosage until it reached equilibrium. Testing a dosage range of 0-10 g for T-A Bent adsorbents revealed that linear adsorption up to 10 g, achieved 94-91% Sn recovery. In these tests, higher adsorbent dosage and increased Sn^{2+} ion recovery medium exhibit a linear increase in adsorption rate. Fig. 9 indicates that activated adsorbents achieved peak adsorption efficiency (87%) at a dosage of 4 g per 20 mL of the bacterial leachate solution.

Effect of Concentration under volume of leached solution

The experiments were performed using an optimal volume of 20 mL per 4 g of adsorbent. T-A-Bent demonstrated the excellent removal efficiency, attributed to its larger pores and higher surface area. However, after a saturation period of 4 h, the tin removal rate decreased from over 96% to 85% with a 20 mL leached sample, as shown in the graphical representation. This decline may be due to the saturation of the adsorbent surface. The results indicate that concentration of the leached sample and the adsorption capacity of the adsorbent surface significantly affect the recovery of tin ions.

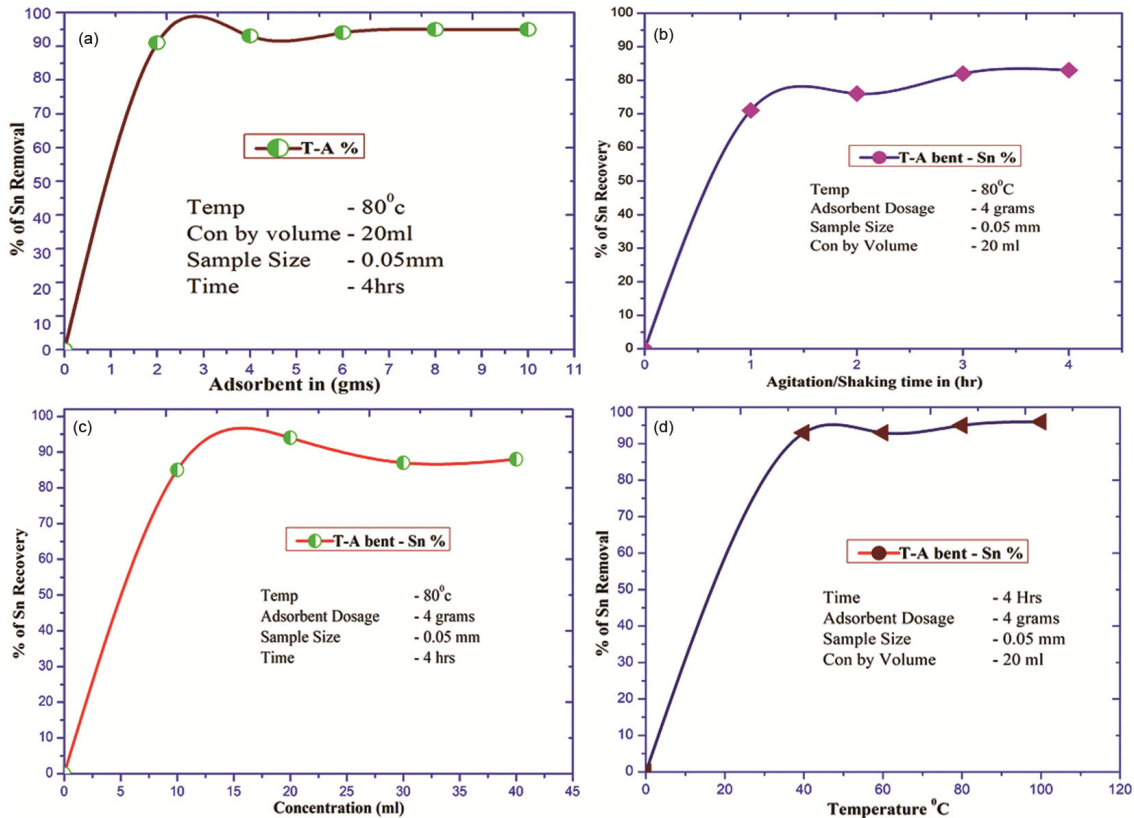


Fig. 9 — Effects of (a) T-A Bent dosage, (b) time, (c) concentration and (d) temperature on Sn^{2+} recovery from leachate solution

Effect of Temperature

The temperature's impact on tin ion adsorption onto Bent samples was explored across temperatures from 20°C to 100°C while keeping other parameters constant. The adsorbent exhibited enhanced tin ion adsorption as the temperature increased from 80°C to 60°C, were increased linearly and getting equilibrium. Post-equilibrium, the adsorption rate decreased, indicating an exothermic sorption process, in line with previous research³⁰. The highest removal quantities of tin ions were observed with T-A Bent at 80°C. Hence, Bacterial leached solution (Co) at 40.7 weight % of tin presence and after adsorption adsorbent having 39.83 weight % of tin, so for retrieving rate as Sn^{2+} 97.86%, which demonstrated greater adsorption rates at higher temperatures.

Two stage operational efficiency for tin recovery

At initial, the optimization was done for tin recovery was performed using RSM study. Consequently, study was report that the developed model was satisfied well with the experiment since it has high correlation coefficient (R^2) 0.9042 for bio-leaching. *Acidithiobacillus ferrooxidans* bacterial leaching revealed that separation

achieved an optimal tin recovery rate of 97.86% under similar conditions like temperature - 29°C, PCBs sample size - 0.25 μm , pulp density - 22.06 g/L and time - 28 days. However, BL showed a higher desirability value (0.845), indicating a marginal preference for bioleaching. In contrast, BL depended on bacterial metabolic activity, with recovery zones exceeding 97.51% (red), 91% (yellow), and 89.86% (blue), highlighting its broader efficiency range. Bacterial leaching provides higher sustainability and efficiency under optimal conditions, making it a promising alternative for tin recovery. Experimental results were found 97.7% under optimized values (leaching duration of 21days, a pulp density of 15 g/L, and a temperature of 20°C). These results followed to reclaim the recovered tin from leachate solution by bentonite clay was 97.86% and finalized the optimized parameters were temperature - 80°C, adsorbent dosage - 4 g, bentonite clay size - 0.05 mm and time - 4 h. These findings suggest that bioleaching is more effective and may serve as a better option for extracting tin from PCBs. Despite the longer time required for bacterial cultivation and growth in bioleaching, it offers higher tin removal efficiency and avoids the use of toxic chemicals, making it a more

environmentally friendly option compared to chemical leaching. Hence, bioleaching is suggested as the preferred method for Sn²⁺ recovery.

Conclusion

This study developed a two-stage sustainable method for tin (Sn) recovery from waste PCBs, combining bacterial leaching using *Acidithiobacillus ferrooxidans* and bentonite clay adsorption. Tin, constituting 42.40 weight% of waste PCBs, was recovered efficiently using environmentally friendly techniques optimized through RSM. Bacterial leaching achieved a recovery rate of 97.33% under optimal conditions - temperature of 29°C, PCB sample size of 0.25 µm, pulp density of 22.06 g/L, and leaching duration of 28 days, with a desirability value of 0.845. Under optimized conditions, experimental results demonstrated a recovery efficiency of 97.33%, indicating the reliability and effectiveness of the process. The experimental bacterial leaching further validated these findings by achieving a tin recovery efficiency of 97.7% under slightly adjusted conditions: leaching duration of 21 days, pulp density of 15 g/L, and temperature of 20°C. This demonstrated the adaptability and strength of bacterial leaching in tin recovery. To reclaim tin ions from bio-leachate, bentonite clay adsorption achieved 97.86% recovery under optimized parameters - temperature of 80°C, adsorbent dosage of 4 grams, particle size of 0.05 mm, and adsorption time of 4 h. This study highlights *Acidithiobacillus ferrooxidans* leaching and bentonite clay adsorption as very good and eco-friendly method for tin recovery, achieving high efficiency while aligning with sustainable recycling goals. The innovative two-stage process addresses waste PCB recycling challenges and promotes a circular economy. Additionally, advanced optimization techniques and predictive models enhance recovery rates under varying conditions.

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