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Research Article

Recovery of copper and plastics from discarded cable waste using vibratory separation: Experimental optimization, statistical modeling, and process evaluation

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Abstract

The recycling of discarded electrical cables is important for recovering valuable copper and reducing the environmental burden of polymeric insulation waste. This study investigates a laboratory-scale vibratory separation system for recovering copper and plastic fractions from mechanically crushed cable waste. The objective was to evaluate the effects of motor speed and table inclination on separation efficiency and to develop statistical models for recovery and purity responses. Controlled 50/50 copper–plastic mixtures were prepared from pre-processed cable waste to ensure reproducible laboratory conditions, while recognizing that this feed is simplified compared with variable industrial cable-waste streams. Tests were conducted at motor speeds of 700–1200 rpm and four inclination configurations based on transverse tilt angle (α) and longitudinal tilt angle (β). The best performance within the tested experimental domain was obtained at α = 8°, β = 0°, and 1000 rpm, yielding copper recovery of 96.63% with 97.67% purity, and plastic recovery of 97.70% with 96.73% purity. Response surface regression models were developed to describe the influence of operating parameters on separation performance. Statistical analysis showed that motor speed and its quadratic term were the dominant factors, while the copper recovery model showed the strongest predictive performance. The results indicate that vibratory separation is a promising dry mechanical approach for copper–plastic separation under controlled laboratory conditions. However, further validation using real industrial feed streams, continuous feeding, dynamic vibration measurements, and energy-consumption analysis is required before broader industrial application can be confirmed.

1. Introduction

The rapid expansion of global electrical and electronic infrastructure has led to a substantial increase in waste electrical and electronic equipment (WEEE), among which discarded electrical cables represent a significant fraction. These cables constitute an important secondary resource due to their high copper content; however, improper disposal practices such as landfilling and open burning result not only in the loss of valuable materials but also in severe environmental pollution through the emission of toxic substances and the persistence of plastic waste [1–4].

Copper is a highly conductive and recyclable non-ferrous metal that plays a critical role in power transmission, electronics, and renewable energy systems. At the same time, polymeric materials such as polyvinyl chloride (PVC) and polyethylene (PE) are widely used as insulating layers in

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electrical cables. The efficient separation and recovery of these materials are therefore essential for resource conservation and for reducing the environmental footprint associated with electronic waste management [5,6]. Among the various recycling technologies, mechanical processing has emerged as a promising approach due to its relatively low energy consumption and minimal environmental impact compared to thermal and chemical methods, which often involve high energy demand and the generation of hazardous emissions [7–10]. In this context, gravity-based separation techniques, including vibratory separation, have gained increasing attention for their ability to exploit density differences between metallic and polymeric components.

Vibratory separation, in particular, relies on the combined effects of oscillatory motion and gravitational forces to induce stratification of particles according to their density and mechanical properties. Previous studies have demonstrated the effectiveness of vibrating tables, jigging systems, and air classification techniques in separating copper from plastic insulation materials such as PVC and polyethylene [11,12]. More advanced approaches, including spouted bed elutriation and vertical vibratory separators, have further improved separation efficiency and process flexibility for different cable waste compositions [13,14]. Additionally, vibratory and gravity-based techniques have been successfully applied to recover residual metals from low-grade fractions, thereby enhancing overall recycling efficiency [15].

Despite these advancements, the efficiency of vibratory separation remains strongly dependent on several factors, including particle size distribution, shape, and operational parameters such as motor speed, used as the controllable vibration-related parameter, and table inclination. The presence of elongated metallic wires and irregular plastic fragments can lead to entanglement and hinder effective stratification, requiring careful optimization of process conditions [16–19]. Furthermore, alternative gravity-based technologies, such as reverse hybrid jigs and magnetic density separation, have been developed to address the challenges associated with materials of similar densities, such as cross-linked polyethylene and conventional plastics [20–22].

Beyond cable recycling, similar physical separation principles have also been successfully applied to other complex waste streams, including printed circuit boards (PCBs), where mechanical beneficiation techniques enable the concentration of valuable metals from heterogeneous mixtures [23–27]. These studies highlight the versatility and robustness of gravity-based separation methods in recycling applications. However, despite the development of several mechanical and gravity-based separation techniques, important limitations remain in the separation of copper and plastic from crushed cable waste. Many previous studies have focused mainly on demonstrating the feasibility of vibrating tables, jigging systems, spouted bed elutriation, or other density-based techniques, while fewer studies have examined the combined influence of motor speed and table inclination on both recovery and purity. In addition, the irregular morphology of crushed cable waste, including elongated copper wires and non-uniform plastic fragments, can affect stratification, particle transport, and separation selectivity. These effects require further experimental and statistical evaluation.

Another important gap concerns the statistical interpretation of vibratory separation performance. In many laboratory-scale studies, separation efficiency is reported mainly through experimental recovery values, while fewer works provide regression-based response models, analysis of parameter interactions, and statistical indicators that describe the reliability of the fitted models. A better understanding of these relationships is necessary to support process improvement and to identify suitable operating conditions within controlled experimental domains. Therefore, the objective of the present study is to investigate the recovery of copper and plastic from mechanically crushed cable waste using a laboratory-scale vibratory separation system. The study evaluates the effects of motor speed, transverse tilt angle (α), and longitudinal tilt angle (β) on copper recovery, copper purity, plastic recovery, and plastic purity. Response surface regression models are developed to describe the influence of these operating parameters and to identify the best separation condition within the tested experimental domain. The novelty of this work lies in combining experimental vibratory separation trials with statistical modeling of both metallic and polymeric product quality, while also considering the influence of particle heterogeneity and operating-parameter interactions.

2. Materials and Methods

2.1. Material Preparation and Characterization

Discarded electrical cables used in this study were supplied by the *Entreprise Nationale de Récupération et Valorisation in Oran, Algeria*. Prior to separation, the cables were manually cut into smaller segments and then processed by mechanical crushing at the same facility. The crushing operation produced a heterogeneous mixture composed of copper wire fragments and plastic particles suitable for laboratory-scale separation tests. However, the degree of liberation was not quantified by microscopic examination or automated image analysis of composite fragments. Therefore, the material should be considered a qualitatively liberated feed, and the possible presence of partially attached copper–plastic composite fragments cannot be excluded.

Although no sieve-based particle size classification was performed, the crushed material was visually inspected and manually examined prior to the separation tests. The particle mixture consisted predominantly of fragments ranging from approximately 2 mm to 15 mm. Copper particles generally appeared as elongated and flexible wire-like fragments with relatively high aspect ratios, whereas plastic particles showed irregular, rigid, and non-uniform geometries. Visual inspection indicated that most metallic and polymeric components appeared physically detached. Nevertheless, some partially attached composite fragments may have remained within the mixture, potentially affecting separation selectivity and experimental variability. The heterogeneous morphology and irregular geometry of the particles are representative of mechanically processed cable waste and can significantly affect granular stratification and vibratory transport behavior [16–19].

Image-based particle-size and shape characterization was performed on representative copper and plastic particles using ImageJ. In total, 217 copper particles and 229 plastic particles were analyzed. The measured descriptors included projected area, maximum Feret diameter, minimum Feret diameter, aspect ratio, circularity, and solidity. The maximum Feret diameter was used as the main two-dimensional particle-size descriptor because both fractions showed irregular, non-spherical morphologies. The particle images were calibrated using a dimensional reference, segmented from the background to produce binary particle masks, and analyzed using the ImageJ particle-analysis functions.

Table 1. Image-based size and shape descriptors of copper and plastic particles

Material	Parameter	Mean ± SD	Median (Q1–Q3)	Range
Copper	Maximum Feret diameter (mm)	4.66 ± 2.05	4.20 (3.23–5.57)	2.05–13.74
Copper	Minimum Feret diameter (mm)	1.62 ± 0.97	1.37 (0.93–2.16)	0.32–6.33
Copper	Projected area (mm^2)	3.27 ± 2.46	2.63 (1.60–3.92)	0.50–14.19
Copper	Aspect ratio	4.20 ± 2.11	3.76 (2.53–5.56)	1.09–11.14
Copper	Circularity	0.290 ± 0.134	0.267 (0.192–0.355)	0.087–0.758
Copper	Solidity	0.608 ± 0.174	0.617 (0.487–0.746)	0.205–0.932
Plastic	Maximum Feret diameter (mm)	3.87 ± 1.45	3.58 (2.71–4.73)	2.01–10.27
Plastic	Minimum Feret diameter (mm)	1.97 ± 0.82	1.80 (1.39–2.38)	0.56–5.48
Plastic	Projected area (mm^2)	4.03 ± 2.99	3.27 (1.85–5.22)	0.69–17.54
Plastic	Aspect ratio	2.39 ± 0.99	2.21 (1.61–2.89)	1.06–6.48
Plastic	Circularity	0.236 ± 0.100	0.222 (0.160–0.297)	0.058–0.541
Plastic	Solidity	0.671 ± 0.103	0.674 (0.603–0.755)	0.388–0.900

Q1 and Q3 denote the 25th and 75th percentiles, respectively. The minimum Feret diameter represents the minimum projected caliper dimension and should not be interpreted as the actual wire diameter or particle thickness.

The density contrast between materials is a key factor governing separation, with copper having a density of approximately 8.9 g/cm^3, while common cable insulation polymers such as PVC and polyethylene exhibit densities in the range of 0.9–1.4 g/cm^3 [11,12]. This density contrast provides the physical basis for gravity-based separation under vibratory conditions. The polymer composition of the plastic fraction was not analytically identified in the present study. PVC and polyethylene are mentioned only as common cable-insulation polymers and should not be interpreted as confirmed polymer types for the tested samples.

2.2. Vibratory Separation Machine Experimental Setup

The vibratory separation machine used in this study is a laboratory-scale apparatus designed to evaluate the separation of copper and plastic particles based on differences in density and mechanical response (Fig. 1).

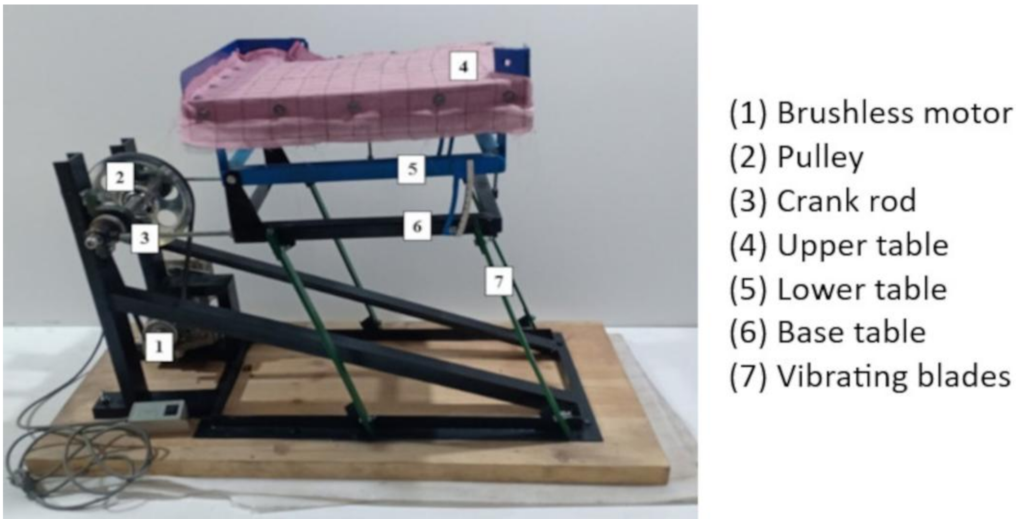

Fig. 1. Vibratory separation machine

Mechanical motion was generated by a 500 W brushless motor (1) rated at a nominal maximum speed of 5000 rpm (220 V, 3.8 A). During the experiments, the speed-control system was used to adjust the motor speed within the range of 700–1200 rpm. The selected speed levels of 700, 800, 900, 1000, 1100, and 1200 rpm correspond to nominal motor rotational frequencies of approximately 11.7, 13.3, 15.0, 16.7, 18.3, and 20.0 Hz, respectively. These values describe the selected motor rotational frequency and should not be interpreted as direct measurements of the actual table oscillation frequency under load. The motor's rotational motion is transmitted via a belt-and-pulley (2) mechanism to a central drive shaft, which actuates two connecting rods (3) attached at each end of the machine. The machine itself consists of three main steel platforms (4, 5, 6) with independent tilt adjustment. Fine angular tuning is accomplished using an integrated screw-guide system, allowing precise control of the platform inclination. This design enables careful manipulation of the flow path and particle trajectory during the separation process.

The operational principle relies on the conversion of rotational energy into horizontal linear vibrations through an eccentric crank-rod mechanism. The eccentricity of the crank was 7 mm, corresponding to a nominal peak-to-peak stroke of approximately 14 mm under ideal direct transmission conditions. However, the actual dynamic displacement of the table was not experimentally measured and may be affected by linkage geometry, mechanical clearance, and operating load. Therefore, the operating speed was considered the main controllable vibration-related parameter in the present study. When a copper–plastic mixture is distributed across the vibrating platform, the combined effects of oscillatory motion and table inclination may promote density-based particle stratification. Denser copper particles may preferentially occupy lower regions of the particle bed, while lighter plastic particles may remain closer to the surface or follow different lateral transport paths. This description represents the inferred operating principle of the apparatus because particle trajectories and bed-layer formation were not directly measured.

Future investigations should include sensor-based vibration monitoring to provide a more complete dynamic characterization of the oscillatory transport mechanism.

The controllable parameters and reproducible operation of this setup make it suitable for laboratory-scale investigations of copper-plastic separation from cable waste. The combination of adjustable operating speed and platform inclination provides flexibility for testing different operating conditions and identifying favorable recovery and purity conditions within the investigated experimental range.

2.3. Experimental Procedure and Feeding Method

Before feed preparation, the crushed material was manually sorted into copper and plastic fractions. The two fractions were weighed separately and recombined to prepare a controlled 50/50 mixture by mass. A total of 200 g of material was used for each experimental trial, consisting of 100 g of copper particles and 100 g of plastic particles obtained from crushed cable waste (Fig. 2).

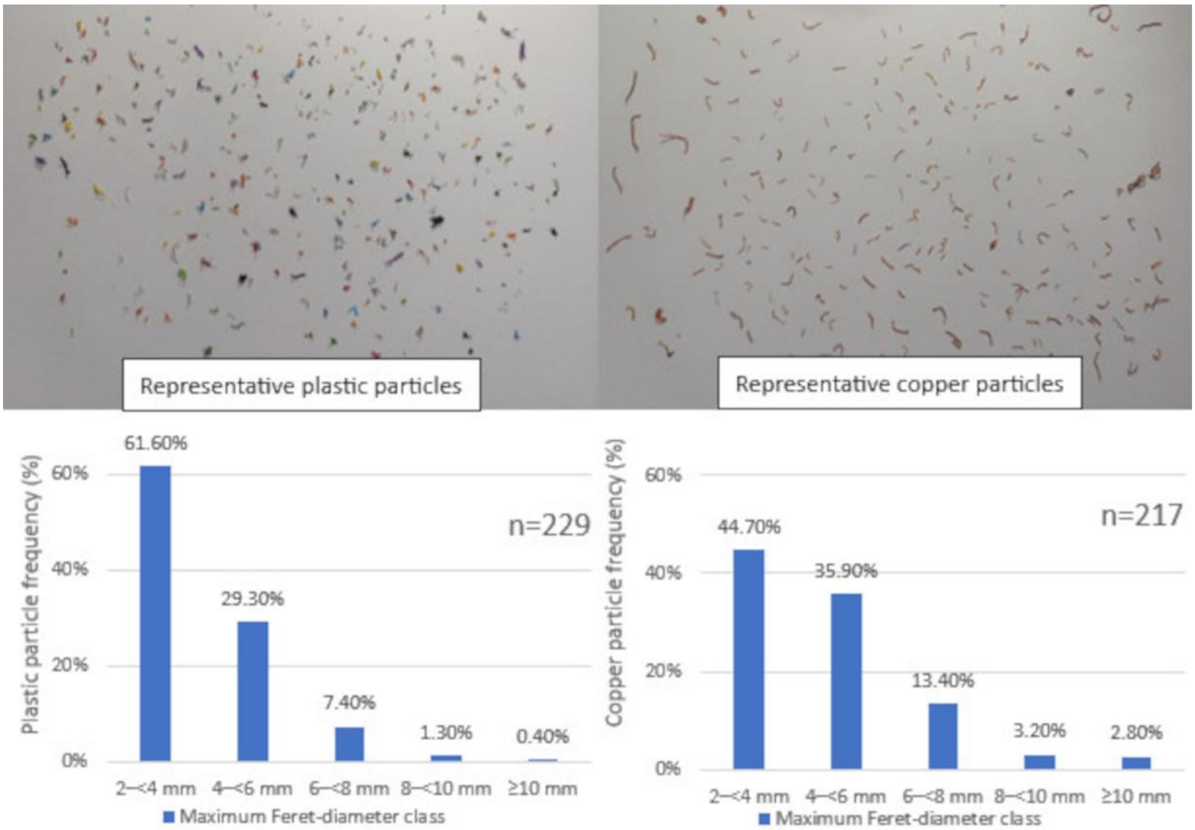

Fig. 2. Image-based characterization of the cable-waste fractions, showing representative plastic and copper particles and their corresponding maximum Feret-diameter distributions for the plastic (n=229) and copper (n=217) fractions

The use of a controlled 50/50 copper–plastic mixture was adopted to ensure reproducibility and to allow direct comparison between experimental conditions. This mixture should be considered a laboratory simplification rather than a direct representation of industrial cable-waste streams, where copper content, polymer type, particle size distribution, and liberation degree can vary significantly. Therefore, the results obtained in this study describe the separation behavior under controlled laboratory conditions and should be validated further using real industrial feed compositions.

No automated feeding system was used in this laboratory-scale study. The material was manually and uniformly distributed across the vibrating platform before each run in order to reduce initial segregation. However, manual feeding may introduce small variations in particle distribution, local bed thickness, and initial particle arrangement. These effects were considered a possible source of experimental variability, particularly for the plastic recovery and purity responses.

The separation process was conducted for 30 seconds under the predefined operating conditions. Preliminary observations indicated that this duration was sufficient to obtain a stable apparent separation pattern, with no appreciable additional improvement observed at longer durations. After each experimental run, each collected product was manually sorted into its copper and plastic components. The component masses were measured separately using a digital balance with a readability of 0.01 g. These measurements were used to determine the recovered masses and contamination masses required for the recovery and purity calculations. The recovery and purity of copper and plastic fractions were calculated using Eqs. (1)–(4), where R_{cu}, P_{cu}, R_{pl}, and P_{pl} represent copper recovery, copper purity, plastic recovery, and plastic purity, respectively:

$$R_{Cu}(\%) = \frac{m_{Cu,r}}{m_{Cu,f}} \times 100 \tag{1}$$

$$P_{Cu}(\%) = \frac{m_{Cu,r}}{m_{Cu,r} + m_{Pl,c}} \times 100 \tag{2}$$

$$R_{Pl}(\%) = \frac{m_{Pl,r}}{m_{Pl,f}} \times 100 \tag{3}$$

$$P_{Pl}(\%) = \frac{m_{Pl,r}}{m_{Pl,r} + m_{Cu,c}} \times 100 \tag{4}$$

where, $m_{Cu,f}$: initial mass of copper in the feed, $m_{Cu,r}$: recovered copper mass, $m_{Pl,f}$: initial mass of plastic in the feed, $m_{Pl,r}$: recovered plastic mass, $m_{Cu,c}$: copper contamination in the plastic fraction, and $m_{Pl,c}$: plastic contamination in the copper fraction.

Each experimental condition was repeated three times under identical operating conditions. For each response variable, namely copper recovery, copper purity, plastic recovery, and plastic purity, the mean value and standard deviation were calculated from the three experimental replicates. The mean values were used for the main performance discussion, while the standard deviations were used to represent experimental variability through error bars in Fig. 3. Variations between replicates were observed, mainly because of heterogeneous particle geometry and the manual feeding procedure. Nevertheless, the principal trends with motor speed and table inclination were generally reproduced across the three replicates. Because the study was based on a limited laboratory dataset, future work should include a more comprehensive uncertainty analysis, including confidence intervals and uncertainty propagation for each response variable.

2.4. Experimental Design

The experimental design evaluated two principal operating factors, namely motor speed and table inclination. Six motor-speed levels and four inclination configurations were investigated.

(a) Effect of motor speed: The motor speed was varied at six levels: 700, 800, 900, 1000, 1100, and 1200 rpm.

(b) Effect of table inclination: Two inclination angles were considered: the transverse tilt angle of the upper table (**α**) and the longitudinal tilt angle of the lower table (β). Four inclination configurations were tested:

- Configuration 1: α = 0°, β = 0°;
- Configuration 2: α = 8°, β = 0°;
- Configuration 3: α = 0°, β = 8°;
- Configuration 4: α = 8°, β = 8°;

It should be noted that only two levels were investigated for each inclination angle (0° and 8°). Therefore, the experimental design allows evaluation of linear and interaction effects between α and β, but it does not allow reliable estimation of quadratic effects for these two angle variables. Consequently, the best condition identified in this study should be interpreted as the best operating condition within the tested experimental domain rather than a general optimum. Additional angle levels would be required in future work to confirm the existence and position of a true optimum region.

Statistical modeling and response surface analysis were performed using Minitab statistical software. The regression analyses were performed using the three replicate observations obtained at each of the 24 operating conditions, providing 72 observations for each response variable. The replicate-level analysis allowed the residual error to be partitioned into lack-of-fit and pure-error components, thereby permitting a formal lack-of-fit assessment. Model performance was evaluated using ANOVA, the residual standard deviation (S), R^2, adjusted R^2, predicted R^2, coefficient p-values, formal lack-of-fit testing, and residual diagnostic plots.

3. Results and Discussion

Image-based characterization confirmed the irregular and non-spherical morphology of both cable-waste fractions. As shown in Table 1 and (Fig. 2), most copper and plastic particles had maximum Feret diameters below 6 mm, indicating that the prepared feed was dominated by relatively small fragments. The copper fraction showed a higher aspect ratio than the plastic fraction, confirming its more elongated wire-like morphology, whereas the plastic particles were generally shorter and irregular. These differences in particle size and shape may affect particle–surface contact, particle orientation, and transport behavior on the vibrating table.

3.1. Effect of Motor Speed and Table Inclination on Copper and Plastic Separation

The experimental results obtained under different motor speeds and table inclination configurations are presented in (Fig. 3), which illustrates the variation of copper recovery, copper purity, plastic recovery, and plastic purity as a function of motor speed for the four tested angle combinations.

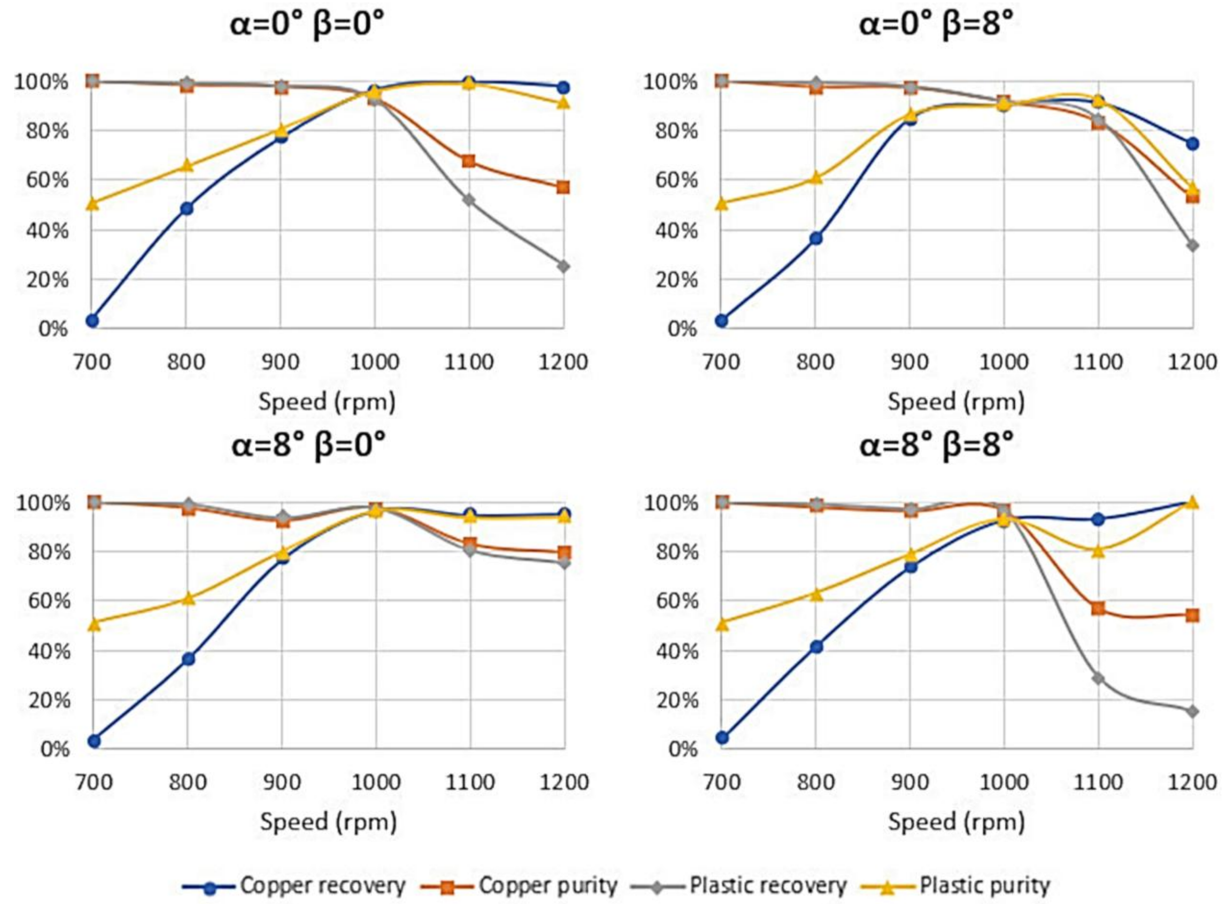

Fig. 3. Variation of copper recovery, copper purity, plastic recovery, and plastic purity with rotational speed (700–1200 rpm) under four α–β angle configurations: (0°, 0°), (0°, 8°), (8°, 0°), and (8°, 8°). Error bars represent ± one standard deviation calculated from three experimental replicates

The error bars in (Fig. 3) indicate the experimental variability obtained from three experimental replicates for each operating condition. Overall, the observed variability did not change the main separation trends with motor speed and table inclination. The intermediate speed range around 900–1000 rpm remained the most favorable region for achieving high recovery and purity, while higher speeds generally increased product contamination. The error bars show the magnitude of experimental variability while also indicating that the principal trends with motor speed and table inclination remained visible across the three replicates.

As shown in (Fig. 3), separation efficiency is strongly dependent on motor speed, which controls the vibration-related excitation and consequently the stratification behavior of the particle mixture. At low motor speeds (700–800 rpm), the observed poor separation suggests that the vibration-related excitation may have been insufficient to overcome inter-particle resistance. Under these conditions, particle movement may have remained irregular and stratification may have been incomplete, contributing to low copper recovery and poor separation performance. This behavior suggests that a minimum level of vibration-related excitation may be required to induce effective density-based segregation. Similar observations have been reported in previous studies on vibratory and gravity separation systems, where insufficient vibration energy prevents the formation of distinct stratified layers [11,14]. As the motor speed increased from 900 to 1000 rpm, a marked improvement in separation performance was observed. At 1000 rpm, copper recovery exceeded 90% for all four inclination configurations, suggesting that the imposed excitation was sufficient to promote particle rearrangement according to density differences. At this stage, denser copper particles may have preferentially occupied lower regions of the particle bed and moved along the inclined surface, while lighter plastic particles may have followed different transport paths because of their lower density and irregular morphology. This interpretation is consistent with the observed recovery and purity trends, although direct particle tracking was not performed [12,17].

The best operating condition within the tested experimental domain was observed at 1000 rpm, where copper recovery reached 96.63%, copper purity reached 97.67%, plastic recovery attained 97.70%, and plastic purity reached 96.73%, as shown in (Fig. 3). This condition represents the best compromise observed within the tested experimental domain between particle mobility and stratification stability, providing high recovery without excessive contamination between fractions. These results are comparable to previously reported values for cable recycling by gravity-based separation [11,12]. However, direct comparison should be made cautiously because feed composition, particle size range, equipment design, throughput, and operating conditions differ among studies. At higher speeds (1100–1200 rpm), copper recovery remains high, but copper purity decreases. The reduction in copper purity may be associated with increased agitation of the particle bed and greater entrainment of plastic particles into the copper-rich fraction. This recovery–purity trade-off is characteristic of vibratory separation systems operating beyond the favorable vibration range observed in this study [17–19]. The influence of table inclination is also clearly visible in (Fig. 3). Among the tested configurations, the combination ($\alpha = 8°$, $\beta = 0°$) produced the best overall separation performance. The transverse inclination may have promoted the directional transport of denser copper particles, while the zero longitudinal angle may have reduced back-mixing and improved separation selectivity. Similar effects of table geometry on particle mobility have been observed in shaking table and jigging processes [12,20].

3.2. Statistical Modeling and Response Surface Analysis

To further describe the system behavior and estimate separation performance within the investigated experimental domain, regression analysis was performed. Mathematical models were established to relate the independent variables transverse tilt angle (α), longitudinal tilt angle (β), and motor speed (S) to the four key response variables: copper recovery, copper purity, plastic recovery, and plastic purity.

Based on the experimental data, the regression equations were developed in uncoded units. The models included linear terms for α, β, and motor speed, the quadratic motor-speed term S^2, and the interaction terms $\alpha\beta$, αS, and βS. In these equations, (Y) represents the predicted value of the response variable expressed as a percentage. The derived equations are given as follows:

Copper Recovery:

$$Y1 = -633.4 - 2.69\alpha + 1.08\beta + 1.3437S - 0.000615S^2 + 0.1155\alpha\beta + 0.00242\alpha S - 0.00205\beta S \quad (5)$$

Copper Purity:

$$Y_2 = -45.4 - 0.99\alpha + 3.27\beta + 0.362S - 0.000228S^2 - 0.1517\alpha\beta + 0.00186\alpha S - 0.00323\beta S \quad (6)$$

Plastic Recovery:

$$Y_3 = -194 + 0.08\alpha + 6.29\beta + 0.703S - 0.000426S^2 - 0.388\alpha\beta + 0.00166\alpha S - 0.00575\beta S \quad (7)$$

Plastic Purity:

$$Y_4 = -264.0 - 3.48\alpha + 2.53\beta + 0.666S - 0.000310S^2 + 0.093\alpha\beta + 0.00351\alpha S - 0.00366\beta S \quad (8)$$

These equations provide a quantitative description of the experimental trends within the investigated operating domain and support interpretation of the effects of motor speed and inclination angles on separation performance. However, the models should not be extrapolated beyond the tested ranges without additional validation experiments. The statistical adequacy of the four regression models was further evaluated using ANOVA, the residual standard deviation (S), R^2, adjusted R^2, predicted R^2, and coefficient significance.

Table 2. Statistical performance and lack-of-fit indicators for the replicate-level regression models

Response variable	S	R^2 %	Adjusted R^2 %	Predicted R^2 %	Model P-value	Main significant terms	Lack-of-fit F-value	Lack-of-fit p-value
Copper recovery	5.86763	98.06	97.21	94.98	<0.001	Speed, Speed^2	21.6	<0.001
Copper purity	7.38269	86.03	79.91	69.05	<0.001	Speed, Speed^2	34.35	<0.001
Plastic recovery	13.8643	82.68	75.10	56.99	<0.001	Speed, Speed^2, α×β	142.94	<0.001
Plastic purity	8.40078	84.44	77.63	53.07	<0.001	Speed, Speed^2	36.70	<0.001

The residual standard deviation (S), calculated as the square root of the residual mean square and expressed in response units, was 5.87, 7.38, 13.86, and 8.40 percentage points for copper recovery, copper purity, plastic recovery, and plastic purity, respectively. Among the four fitted models, copper recovery showed the smallest residual dispersion, whereas plastic recovery showed the largest. As shown in Table 2, all four regression models were statistically significant ($p < 0.001$). Motor speed and its quadratic term were identified as the main significant factors for all four responses, confirming the nonlinear influence of rotational speed on separation performance. Among the interaction terms, only the α×β interaction was identified as significant for plastic recovery, whereas no interaction terms were listed as significant for the other responses. However, the formal lack-of-fit tests were also significant for copper recovery ($F = 21.60$, $p < 0.001$), copper purity ($F = 34.35$, $p < 0.001$), plastic recovery ($F = 142.94$, $p < 0.001$), and plastic purity ($F = 36.70$, $p < 0.001$). These results indicate that, although the models explained a substantial proportion of the experimental variation, the selected polynomial structure did not fully capture all systematic variation in the responses. This behavior is not unexpected for a second-order response surface model applied to a separation process governed by complex particle interactions and limited experimental factor levels. The strongest lack-of-fit was observed for plastic recovery. Consequently, the models should be used mainly to describe experimental trends and parameter effects within the investigated domain rather than as fully validated predictive models. Additional inclination levels, alternative model structures, and independent validation experiments are required to improve model adequacy and predictive reliability.

Residual diagnostic plots for the four replicate-level regression models, based on the 72 observations, are provided in (Fig. S1–S4) of the Supplementary Material. The normal probability plots showed approximate linearity for all responses, although moderate deviations were observed at the distribution tails and several standardized residuals exceeded approximately ±2. The residuals-versus-fitted plots did not exhibit a simple funnel-shaped pattern; however, clustering and systematic response-dependent structures were observed, particularly for plastic recovery and, to a lesser extent, for copper purity and plastic purity. The residuals-versus-order plots also showed grouped runs and abrupt changes. Because the observations were arranged by operating condition rather than by a randomized experimental run sequence, these plots were not interpreted as strong evidence of residual independence. Overall, the diagnostics suggest that approximate residual normality was broadly acceptable, whereas constant variance and model-form adequacy were only partially supported. This interpretation is consistent with the significant lack-of-fit tests. The unusual observations were retained because no measurement or data-entry errors were identified.

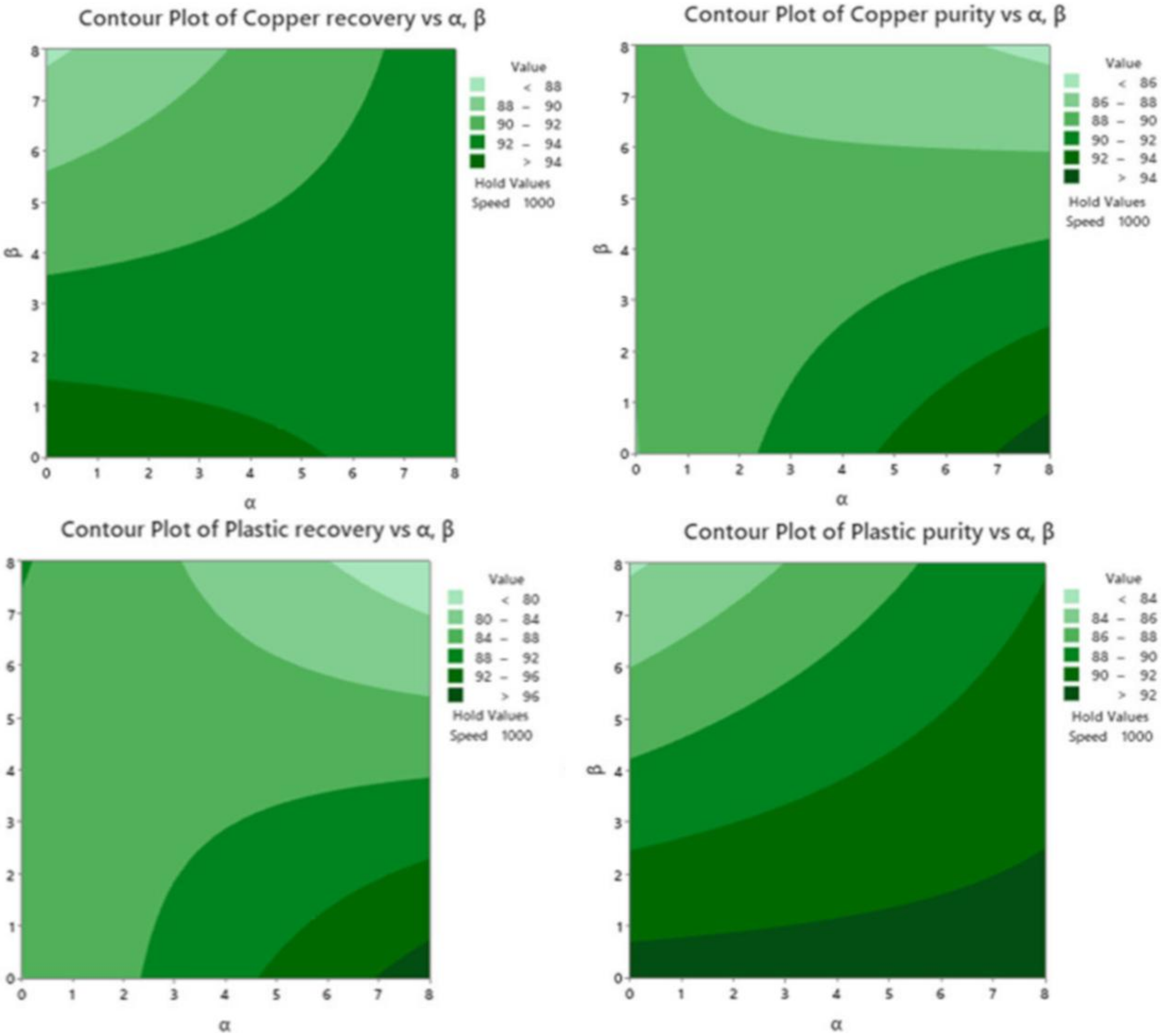

Fig. 4. Contour plots of copper recovery, copper purity, plastic recovery, and plastic purity as a function of tilt angles (α, β) at a fixed speed of 1000 rpm

The inclusion of standard-deviation error bars in (Fig. 3) provides additional experimental reliability information and helps distinguish consistent trends from variability caused by manual feeding and heterogeneous particle morphology. In addition, because only two levels of α and β were tested, the quadratic terms α^2 and β^2 could not be estimated and were removed from the response surface models. This limitation should be considered when interpreting the contour and surface plots. To visualize the effect of table inclination at the selected motor speed, contour and surface plots were generated by maintaining the motor speed constant at 1000 rpm. The contour plots in Fig. 4 illustrate the distribution of performance indicators across the α–β domain, providing an exploratory visualization of the model-predicted response variation within the investigated α–β domain.

As shown in Fig. 4, the contour plots indicate a model-predicted favorable region within the investigated α–β domain. For copper recovery, the highest predicted contour values are concentrated near the region corresponding to a transverse tilt angle of 8° and a longitudinal tilt angle of 0°. This agrees with the experimental results obtained under the tested conditions, where the α = 8° and β = 0° configuration produced the highest copper recovery. Similarly, the contour plots for copper purity, plastic recovery, and plastic purity suggest that the same region provides favorable separation performance within the tested domain. However, these plots should be interpreted as model-based interpolations rather than direct experimental confirmation of all possible α–β combinations.

The surface plots in Fig. 5 further illustrate the model-predicted variation in separation performance across the investigated α–β domain. The favorable regions shown in the response surfaces should be interpreted only as exploratory model-based interpolations within the tested range. Additional angle levels and validation experiments would be required to determine whether the predicted favorable region persists across a more densely sampled inclination domain and whether an interior optimum exists.

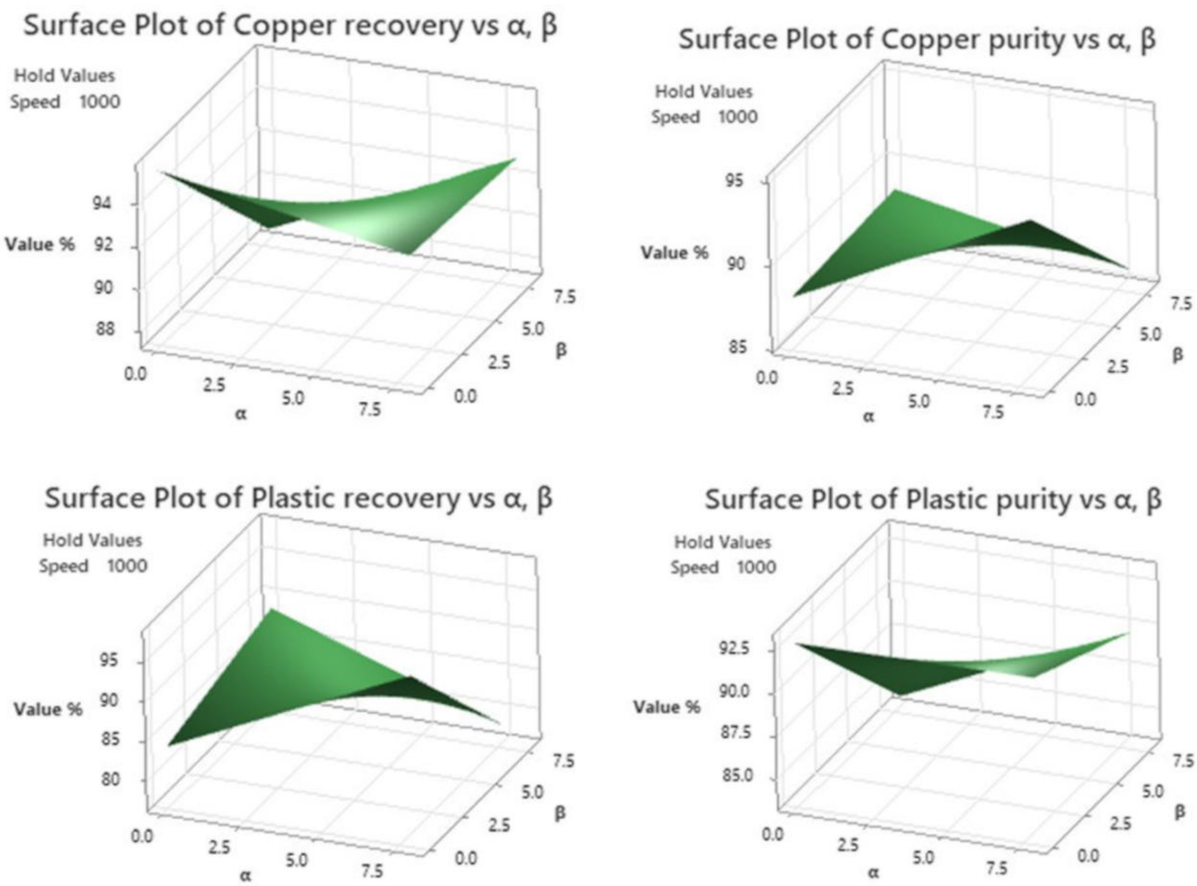

Fig. 5. Surface plots of copper recovery, copper purity, plastic recovery, and plastic purity as a function of tilt angles (α, β) at a fixed speed of 1000 rpm

It should also be emphasized that the contour and surface plots are model-based interpolations within the tested α–β domain. They should not be interpreted as experimental confirmation of all possible angle combinations. Since only two levels of α and β were investigated, the best condition identified in this study corresponds to the best operating condition within the tested experimental range. However, it should be noted that the models were developed based on a limited experimental dataset and have not yet been validated under independent operating conditions. Future studies should therefore include additional experiments and validation procedures to assess the robustness and general applicability of the proposed models, particularly for large-scale industrial applications.

3.3. Physical Interpretation of the Separation Mechanism

Under vibratory motion, repeated oscillations may promote particle rearrangement within the mixture. Owing to their higher density and inertia, copper particles may preferentially occupy lower regions of the particle bed and maintain greater contact with the vibrating surface. In contrast, lighter plastic particles may follow different upward or lateral transport paths. This density-based interpretation provides a plausible qualitative explanation for the observed separation trends. The results suggest that the excitation associated with 1000 rpm was sufficient to promote stratification without excessive mixing. At lower speeds, limited particle mobility may have restricted stratification, whereas higher-speed excitation may have increased mixing and reduced product purity. Although direct motion tracking or high-speed imaging was not performed in this study, the observed trends are consistent with established theories of granular segregation and vibratory transport [14,17].

The separation mechanism discussed above should be interpreted as a qualitative explanation based on the observed recovery and purity trends rather than direct dynamic measurement. In this study, particle trajectories, vibration amplitude, acceleration, and bed-layer formation were not measured using high-speed imaging or motion sensors. Therefore, the proposed explanation of density-driven stratification and particle rearrangement remains inferential. Nevertheless, the observed dependence of separation efficiency on motor speed and table inclination is consistent with established granular segregation behavior, where differences in density, inertia, particle shape, and frictional interaction influence vertical stratification and directional transport. Future work should include high-speed particle tracking and sensor-based measurements of table displacement, vibration amplitude, acceleration, and operating frequency under load to validate the detailed particle-migration mechanism.

3.4. Limitations and Perspectives for Industrial Application

While the experimental results demonstrate the effectiveness of the vibratory separation system, several limitations must be acknowledged. First, the experiments were conducted at laboratory scale using 200 g batches, which limits direct extrapolation to industrial processing conditions. Second, the feed composition consisted of an equal copper–plastic mass ratio, which does not fully represent the variability of actual cable waste streams. In addition, the absence of direct measurement of vibration amplitude, acceleration, and energy consumption restricts the precision of process characterization and limits comparison with alternative technologies.

Despite these limitations, the process presents several potential advantages that may be relevant for future industrial development. Because the separation is performed under dry conditions, the process does not require water or chemical reagents during laboratory operation. This suggests a potential environmental advantage compared with wet or chemical treatment routes. However, a complete environmental assessment would require direct measurement of energy consumption, emissions, throughput, and material losses. The use of a 500 W motor and a mechanically simple design suggests possible operational advantages. Nevertheless, energy consumption per unit mass, maintenance requirements, and economic performance were not directly quantified in this study. Therefore, claims regarding energy efficiency and cost effectiveness should be considered preliminary.

Furthermore, an independent experimental validation dataset was not available to evaluate the predictive performance of the developed response surface models. Consequently, the predictive capability of the models should be interpreted within the investigated experimental domain. Future studies should include independent validation experiments using additional operating conditions to further assess the robustness and generalizability of the proposed models.

Scale-up may be possible through larger vibrating platforms or continuous-feed systems. However, industrial applicability requires further investigation using realistic feed compositions, continuous feeding, feed-rate variation, higher throughput, equipment-wear monitoring, long-term stability testing, and pilot-scale validation. Therefore, the present system should be considered a laboratory-scale proof-of-concept rather than an industrially validated separation process.

4. Conclusions

This study investigated the recovery of copper and plastic from discarded electrical cable waste using a laboratory-scale vibratory separation system. The results showed that separation performance was strongly affected by motor speed and table inclination. Within the investigated experimental domain, the best operating condition was obtained at a motor speed of 1000 rpm, a transverse tilt angle (α) of 8°, and a longitudinal tilt angle (β) of 0°. Under these conditions, copper recovery reached 96.63% with a purity of 97.67%, while plastic recovery and purity reached 97.70% and 96.73%, respectively. These results indicate that vibratory separation can provide effective separation of copper and plastic fractions under controlled laboratory conditions.

Response surface regression models were developed to describe the influence of motor speed and inclination angles on recovery and purity. The statistical analysis showed that motor speed and its quadratic term were the most influential factors affecting separation performance. The copper recovery model showed the strongest predictive performance, while the models for copper purity, plastic recovery, and plastic purity showed moderate predictive ability. Therefore, the regression models are useful for describing the experimental trends within the tested operating range, but they should not be considered universal predictive models without additional validation.

The proposed process has several potential advantages, including dry operation, mechanical simplicity, and the possibility of reducing water and chemical use compared with wet or chemical separation routes. However, these advantages should be interpreted as potential benefits rather than confirmed industrial outcomes, since energy consumption, economic feasibility, environmental impact, humidity effects, equipment wear, and long-term stability were not directly measured in this study. In addition, the experiments were conducted using controlled 50/50 copper–plastic mixtures and laboratory-scale batch feeding, which limits direct extrapolation to industrial cable-waste streams.

Future work should focus on pilot-scale validation, continuous feeding, expanded sieve-based particle-size distribution analysis, quantitative liberation assessment, polymer-type identification, vibration-amplitude, acceleration, table-displacement, and operating-frequency measurements under load, energy-consumption analysis, equipment-wear evaluation, and testing with real industrial cable-waste mixtures.

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