A Comparative Analysis of Density and Electrostatic Separation Techniques for Recycling Copper and Plastic from Cable Waste

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ABSTRACT

The recycling of cable waste is essential for sustainable material management, given its substantial content of valuable resources, such as copper and plastic. This study compares two separation methods: the mechanical separation (density-based separation) and electrostatic separation, for the efficient recovery of copper and plastic from cable waste. Laboratory-scale trials using a density table and a roll-type electrostatic separator were conducted to assess the performance, focusing on the influence of varying operational parameters. The results show that density separation achieved copper recovery rates up to 96.5% under optimal conditions, demonstrating significant resilience to environmental humidity fluctuations. In contrast, electrostatic separation produced high-purity fractions at optimized settings (28 kV, 80 rpm), but its efficiency was significantly compromised under elevated humidity due to increased plastic particle conductivity. Based on this study, a hybrid strategy that integrates both techniques to enhance recycling efficiency in industrial-scale operations is proposed.

Keywords-cable waste recycling; copper recovery; density separation; electrostatic separation; plastic separation; hybrid recycling techniques

I. INTRODUCTION

The proliferation of electrical and electronic devices has led to an increase in cable waste generation, posing both environmental and economic challenges worldwide. Cable waste typically contains valuable materials, particularly copper and plastic, making its recycling a crucial part of sustainable waste management practices. Copper, a metal with outstanding electrical conductivity, is essential for power transmission and communication systems, whereas plastic serves as insulation but frequently accumulates in landfills, thereby exacerbating long-term environmental pollution [1-5].

Mechanical recycling has emerged as a promising strategy to address the environmental challenges associated with cable waste. Unlike chemical or thermal recycling methods, which often require high energy inputs and may release harmful byproducts [6-8], such as in steam gasification of PVC cables [9] or ammonium salt leaching for electronic waste [10], mechanical approaches are more cost-effective and scalable for industrial use. Among these, density separation stands out as a particularly attractive technique, based on the density differences between the copper and plastic particles to achieve efficient material separation. The density separation table operates by combining controlled vibration with an adjustable tilt angle, which induces particle sorting based on density.

Density tables are widely used in electric cable recycling, mineral processing, and agricultural industries. Studies on density and gravity separation for electronic wastes and PCBs [11-14] use methods like wet impact crushing and air classification, with particle size distribution being critical for effective metal recovery. Jig separation research [15-20] focuses on improving efficiency for plastics and cables through particle geometry and advanced jig designs, such as reverse hybrid jigs and continuous-type jigs with restraining walls. Magnetic density separation studies [21] explore the challenges in cable recycling and innovative granular waste sorting processes.

In parallel, electrostatic separation leverages electrical conductivity differences, using high-voltage fields to separate metal-plastic mixtures. Authors in [22, 23] investigated the particle size effects on separating granular plastics using belt-type corona separators. Plate-type separators [24, 25] optimize the recovery of metals and plastics from cable wastes. Various devices [26, 27], including rotating disks, double-sided actuators, and electrical curtains, enable the efficient separation of metal/plastic mixtures. Other methods [28, 29] involve vertical vibratory separation and vibrating electrical curtains for isolating copper and plastic particles. General cable recycling studies [30, 31] focus on sustainable PVC and copper recovery approaches.

Although both density and electrostatic techniques have proven effective in cable recycling, few studies compare their performance under similar conditions. Most research focuses on optimizing a single method in isolation, often overlooking environmental factors such as humidity.

This study aims to systematically compare both methods for copper and plastic recovery from cable waste. For density separation, the variable/parameters include motor speed (700–1200 rpm) and table inclination angles (α and β, ranging from 0° to 4°), selected for their direct influence on vibration intensity and gravitational forces, which are critical for separation efficiency. For electrostatic separation, the variable parameters include applied voltage (up to 28 kV) and roll electrode speed (up to 80 rpm), selected because they govern the corona discharge and particle throughput, respectively, which are essential for effective charge-based separation. For both techniques, the constant parameters include sample mass (40 g) and humidity levels (45% and 65% RH), chosen to standardize the experimental conditions.

II. MATERIALS AND METHODS

Two experimental laboratory setups were used in the study to investigate and compare the efficiency of two different separation techniques for recovering copper and plastic from waste cable materials: a density separation table, which uses differences in particle density and mechanical behavior, and a roll-type electrostatic separator, which utilizes electrostatic charging and induction principles to achieve selective separation based on electrical conductivity.

A. Density Table- Experimental Setup

The laboratory-scale density separation table, as shown in Figure 1, is designed to separate metallic and plastic particles based on density differences. It features adjustable settings for vibration intensity and table inclination, powered by a 550 W brushless motor (4500 rpm, 220 V, 3.8 A). The motion of the motor is transmitted via a belt-and-pulley system to a central shaft with two connecting rods. An integrated screw-guide mechanism allows precise control of the platform's upper and lower tilt angles.

The dimensions of the main components of the density separation table are:

- Upper table: 500 mm (length) × 410 mm (width)
- Lower table: 500 mm (length) × 410 mm (width)
- Vibrating blades: 500 mm (length) × 30 mm (width) × 6 mm (thickness)

The system generates linear oscillations that convert the motor output into horizontal vibrations. As the copper–plastic mixture moves over the inclined surface, the higher-density copper particles preferentially settle and migrate downward, whereas the lower-density plastic fractions remain near the surface or are displaced laterally. Separation is driven by gravitational force, vibrational dynamics, and directional flow.

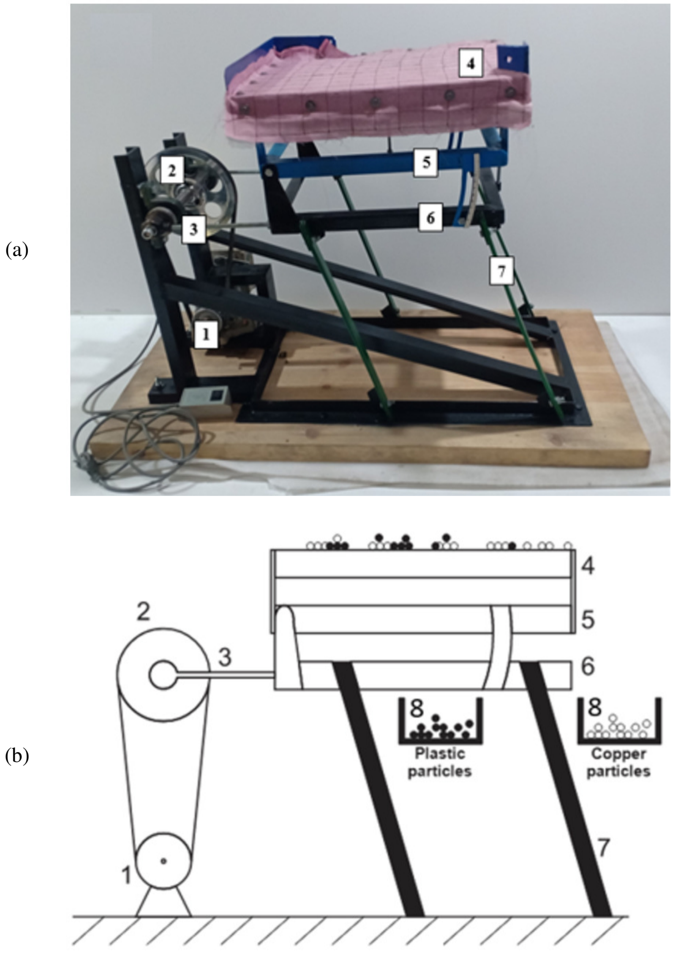


Fig. 1. Density separation table: (a) photograph, (b) descriptive schematic: (1) Brushless motor, (2) Pulley, (3) Crank rod, (4) Upper table, (5) Lower table, (6) Base table, (7) Vibrating blades, (8) Collecting hoppers.

A representative 40 g sample, as depicted in Figure 2, comprising equal proportions of copper particles (20 g) and plastic particles (20 g), was used in each experimental run. The material was supplied by the Entreprise Nationale de Récupération et Valorisation (Oran, Algeria) and was sourced from discarded electrical cable waste. All samples were weighed using an electronic balance with a measurement precision of 0.01 g.

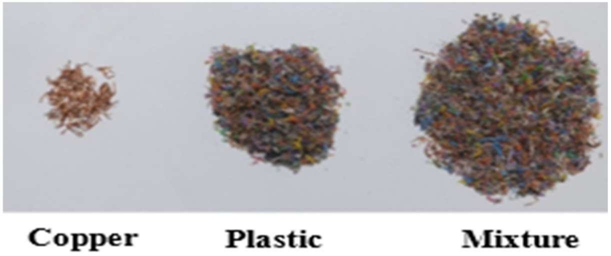


Fig. 2. Representative samples.

The separation procedure involved evenly distributing the copper-plastic mixture on the surface of the separation table, followed by a 2-minute run at the designated tilt angle and motor speed. After each run, the separated fractions were collected and weighed to calculate the recovery and purity rates for copper and plastic.

The experimental program was divided into two phases: speed variation tests and angle variation tests.

1) *Speed Variation Tests*

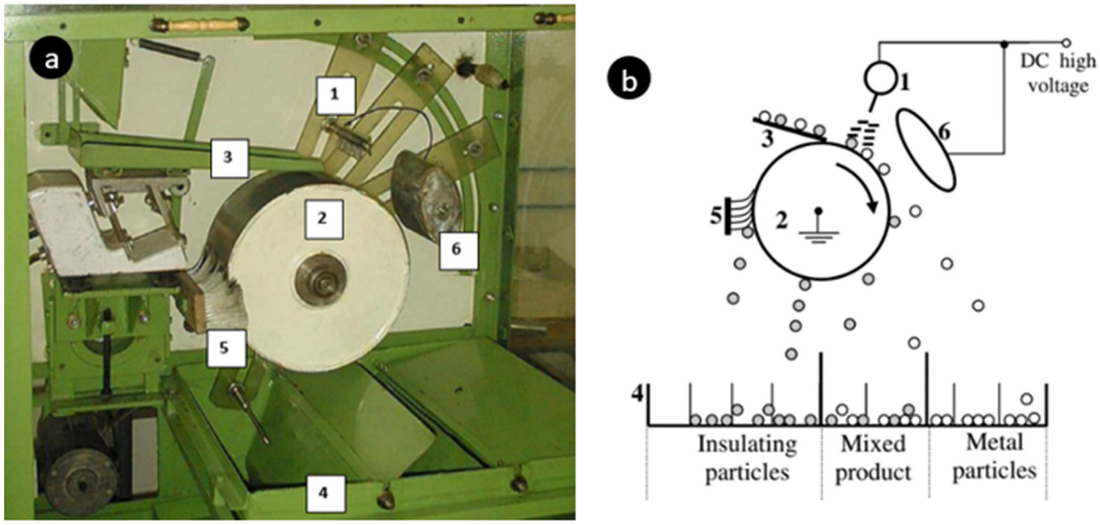
For each fixed combination of the upper and lower table angles, the motor speeds were systematically varied across 700, 800, 900, 1000, 1100, and 1200 rpm. This phase evaluated the direct impact of the rotational speed on the separation performance.

2) *Angle Variation Tests*

In the second phase of experimentation, the motor speed was kept constant to isolate the effect of the table inclination on the separation performance. To enable a systematic evaluation of the influence of individual slope adjustments on the separation performance, the tilt angle of either the upper or lower segment was varied across 0°, 2°, and 4°, whereas the other one remained fixed.

B. *Electrostatic Separator Experimental Setup*

The electrostatic separation system used in this study was a laboratory-scale roll-type separator, as shown in the photographic image in Figure 3(a) and schematically illustrated in Figure 3(b). The system functions by generating and controlling electric charges through the combined mechanisms of corona discharge and electrostatic induction, enabling the selective separation of metal and plastic particles.



(a) Photography; (b) Descriptive schematic; (1) Corona electrode, connected to a high-voltage direct current (DC) power supply; (2) Grounded rotating cylindrical electrode; (3) Electromagnetic vibratory feeder for particle delivery; (4) Collecting hoppers for separated materials; (5) Mechanical brush for cleaning residual particles from the cylinder surface; (6) Static electrode, connected to the same high-voltage supply as the corona electrode

Fig. 3. Roll-type electrostatic separator.

The dimensions of the main components of the laboratory-scale electrostatic separator are:

- Rotating roll electrode: 350 mm (diameter) × 150 mm (length)
- Vibratory feeder: 100 mm (width)
- High-voltage electrodes: 150 mm (length)

A high-voltage DC power supply energizes a corona electrode (1) equipped with sharp emitting tips. This electrode ionizes the surrounding air, producing a corona discharge that imparts surface charges to particles introduced into the separation zone.

Cable waste particles comprising a mix of conductive (copper) and insulating (plastic) materials are fed onto the surface of a grounded, rotating cylindrical electrode (2) using an electromagnetic vibratory feeder (3). Upon contact with the corona discharge field, the particles acquire charges of the same polarity as the applied voltage. Their behavior during separation is dictated by their electrical conductivity.

Insulating particles, being poor conductors, retain the acquired charge. The resulting force causes them to adhere to the rotating drum's surface. These particles remain attached until gravity overcomes the adhesive electrostatic force. At this point they detach and fall into a designated collector bin (4). A mechanical brush (5) is positioned at the end of the drum's rotation path to remove any particles that remain attached to the surface.

Conductive particles, such as copper, immediately discharge upon contacting the grounded drum surface. As these particles enter the region influenced by the static electrode (6), which is an elliptically shaped electrode connected to the same high-voltage source, they undergo electrostatic induction. This causes them to acquire a charge of opposite polarity, resulting in a strong attraction toward the field generated by the static electrode.

In the experiments conducted using the laboratory roll-type electrostatic separator, a similar sample mass of 40 g was used. The particles were deposited onto the vibratory feeder, which ensured a controlled and uniform feed rate onto the rotating roll. The experiments examined two primary operational parameters: applied high voltage and rotational speed of the electrode.

In this study, the variable parameters included the motor speed and inclination angles of the density separation table, as well as the applied voltage and roll electrode speed of the electrostatic separator. The constant parameters included the sample mass and humidity levels (45% and 65% RH). For the electrostatic setup, the particle flow rate and vibration amplitude of the feeder were also kept constant to ensure stable feeding conditions.

After separation, the metal and plastic fractions were collected separately and weighed. These measurements were then used to calculate the recovery and purity rates of copper and plastic achieved by the separator.

III. RESULTS AND DISCUSSION

A. *Density Separation Table*

Preliminary experiments were conducted under fixed values of the table inclination angles, α (upper table) and β (lower table), while varying the motor speed between 700 and 1200 rpm. The obtained results, representing the mean values derived from the experiments, are presented in Table I.

The density table experiments showed that plastic separation was less efficient than copper, due to differences in particle density and behavior. The copper recovery improved with increasing motor speed, exceeding 90% at 1000–1100 rpm and attaining a maximum of 99.5%. The optimal operating condition was identified at 1000 rpm with tilt angles, $\alpha = 4°$ and $\beta = 0°$, yielding 96.5% recovery and 97.47% purity.

TABLE I. RECOVERY AND PURITY RESULTS UNDER DIFFERENT ROTATIONAL SPEEDS FOR DIFFERENT INCLINATION ANGLE CONFIGURATIONS (HUMIDITY RH= 45%)

Case	Rate (%)	Speed (rpm)					
		700	800	900	1000	1100	1200
$\alpha = 0° \beta = 0°$	Copper recovery	3.5000	48.00	76.50	96.00	99.50	97.50
	Copper purity	100.00	97.96	97.45	92.75	67.23	56.69
	Plastic recovery	100.00	99.00	98.00	92.50	51.50	25.50
	Plastic purity	50.890	65.56	80.66	95.85	99.04	91.07
$\alpha = 0° \beta = 4°$	Copper recovery	3.0000	36.00	84.50	90.00	91.00	74.50
	Copper purity	100.00	97.30	97.13	91.37	83.21	52.84
	Plastic recovery	100.00	99.00	97.50	91.50	84.50	33.50
	Plastic purity	50.760	60.74	86.28	90.15	92.32	56.78
$\alpha = 4° \beta = 0°$	Copper recovery	3.5000	36.00	76.50	96.50	94.50	95.00
	Copper purity	100.00	97.30	92.17	97.47	82.89	79.50
	Plastic recovery	100.00	99.00	93.50	97.50	80.50	75.50
	Plastic purity	50.890	60.74	79.91	96.53	93.60	93.79
$\alpha = 4° \beta = 4°$	Copper recovery	4.0000	41.50	73.50	92.50	93.00	100.00
	Copper purity	100.00	97.65	96.08	96.35	56.71	54.05
	Plastic recovery	100.00	99.00	97.00	96.50	29.00	15.00
	Plastic purity	51.020	62.86	78.54	92.79	80.56	100.00

Compared to the findings in [1], where 93.5% recovery was achieved using water-based gravity separation, this dry process offers similar efficiency while being more cost-effective, sustainable, and water-free. However, speeds above 1200 rpm caused excessive vibration frequency, leading to plastic contamination and reduced copper purity, confirming the known recovery–purity trade-off [12, 28]. Purity was the highest at moderate speeds and declined at higher speeds. The instability observed between 1000 and 1200 rpm can be attributed to the motor speed being too high, making it too powerful for the equipment's design limits; increased vibration frequency, which disturbs the orderly stratification of copper and plastic particles; and the reduced residence time of particles on the separation table at higher speeds, limiting the efficiency of density-based stratification. Together, these effects compromise the separation selectivity and lead to unstable performance in this operating range.

Based on this, a motor speed of 1000 rpm was adopted as the optimal setting for subsequent experiments. Figure 4 depicts the mean values of the effect of varying the upper tilt angle (α) at two humidity levels (45% and 65% RH), with the lower tilt angle (β) fixed at 0° and 4°, illustrating recovery and purity trends for both materials.

Figure 4 demonstrates that increasing the upper (α) or lower (β) tilt angle from 0° to 4°, while maintaining the other parameter constant, improved both the copper recovery and plastic purity. Greater inclination enhanced the gravitational and inertial forces, promoting better separation by stabilizing the copper trajectories and improving the plastic stratification. However, beyond a certain angle, efficiency may be reduced due to particle instability—though this limit was not reached in this study.

Additionally, the results under 45% and 65% humidity revealed that the density separation is unaffected by humidity, as it relies on intrinsic material densities, which remain stable despite the moisture changes.

B. Electrostatic Separation

The initial tests aimed at optimizing the applied high voltage (*V*) and roll electrode speed (*N*) for electrostatic separation. Both the copper and plastic purity and recovery improved with increasing voltage, plateauing at 28 kV—the maximum safe limit before electrical breakdown. This aligns with the corona discharge theory, where ionization efficiency approaches saturation [25].

The performance of the electrostatic separator was evaluated by varying the rotational speed of the cylindrical roll electrode, as portrayed in Figure 5. Purity rate was used as a key indicator, with particular attention paid to the effect of the centrifugal force.

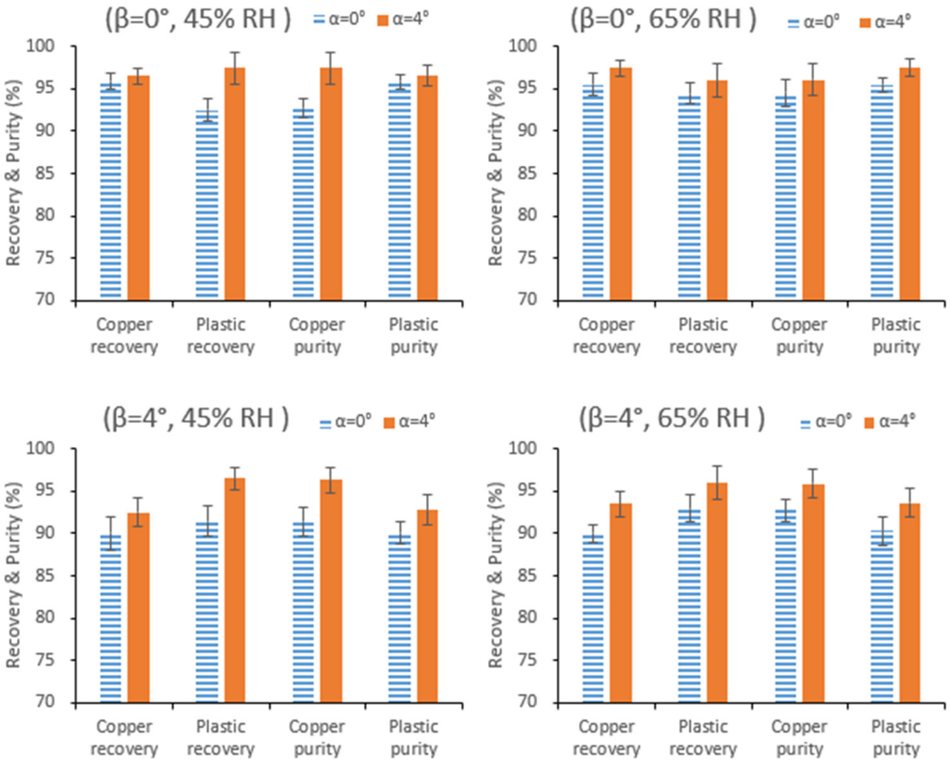


Fig. 4. Effect of tilt angle on the recovery and purity of copper and plastic using density separation at 1000 rpm under different humidity conditions.

Figure 5 illustrates how the copper purity varies with the rotating roll speed in the electrostatic separator. At lower speeds (40-80 rpm), the purity remains very high (≈ 95-97%) because conductive particles have sufficient contact time with the grounded drum. Beyond 80 rpm, the purity begins to decline, and the drop becomes pronounced above 120 rpm. The main factor responsible for this decline is the increasing centrifugal force, which detaches the plastic particles prematurely from the roll surface. As a result, some plastic particles are misclassified, contaminating the copper fraction.

The final tests used the optimal settings (28 kV, 80 rpm) under two humidity levels (45% and 65%). Figure 6 displays the mean values from the tests. Lower humidity improves the electrostatic separation by reducing the surface conductivity, enhancing the charge retention on insulating plastics. At higher humidity (65% RH), plastic absorbs moisture, becoming partially conductive and disrupting separation [22, 27]. This study shows a more pronounced drop in the plastic recovery, most likely due to particle size or surface differences.

Under optimal conditions (28 kV, 80 rpm, 45% RH), the high-purity recovery of both copper and plastic is achievable. Ambient humidity significantly impacts electrostatic efficiency and must be managed in large-scale systems. In contrast, density separation is unaffected by humidity, as it relies solely on physical properties like density and vibration. This makes it more robust and suitable for use in uncontrolled industrial environments.

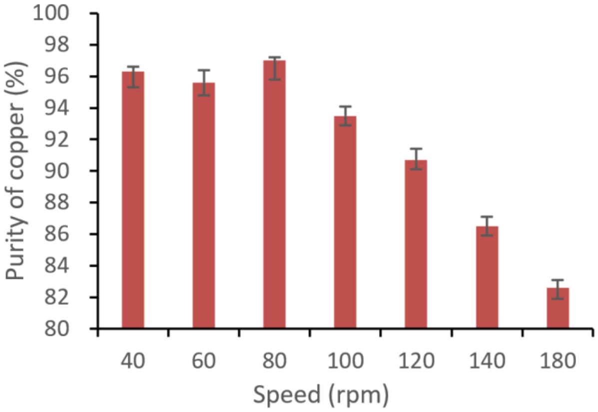


Fig. 5. Variation of the purity of the copper as a function of the rotational speed of the cylindrical rotating electrode.

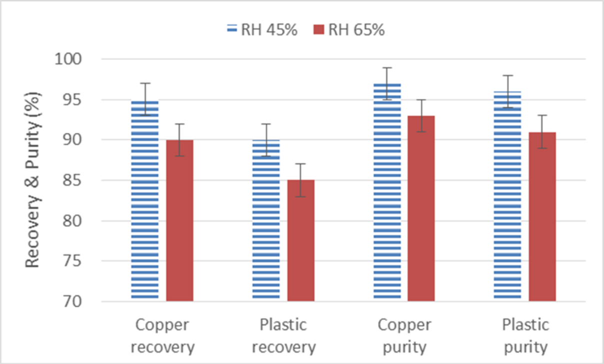


Fig. 6. Effect of ambient humidity on recovery and purity rates in electrostatic separation of copper and plastic particles.

C. Optimal Selection of the Separation Technique

The choice between density and electrostatic separation depends on the operating conditions and desired outcomes. Density separation is more robust, cost-effective, and stable even in humid environments, making it suitable for large-scale or outdoor applications. In contrast, electrostatic separation offers higher purity under controlled, low-humidity environments, fitting indoor facilities.

A hybrid recycling strategy, integrating the density separation table for processing large volumes of shredded cable waste, followed by electrostatic separation to refine the copper recovery from the resultant middling fractions, is proposed as an optimal approach. This synergistic methodology could enhance the overall copper recovery and purity by capitalizing on the environmental resilience of the density separation and the precision of the electrostatic separation, thereby offering a versatile and efficient solution for large-scale cable waste recycling systems.

IV. CONCLUSION

This study provides a comprehensive comparative assessment of two prominent mechanical recycling techniques, density separation and electrostatic separation, for the recovery of copper and plastic from cable waste. A total of 48 experiment runs were conducted using the density-based method and 12 runs using the electrostatic method, enabling a detailed evaluation of performance under varied operational and environmental conditions.

The density separation technique delivered consistently high performance across a range of motor speeds and tilt angles, with a peak copper recovery of 96.5% and purity of 97.47% at the optimal configuration (1000 rpm, $\alpha = 4°$, $\beta = 0°$). Importantly, its performance remained stable even under elevated humidity conditions, highlighting its insensitivity to moisture and strong suitability for deployment in variable or uncontrolled field environments. Furthermore, its dry, water-free operation enhances sustainability by minimizing the processing costs and eliminating the need for wastewater management requirements.

In contrast, the electrostatic separation method achieved high-purity fractions under optimal conditions of (28 kV and 80 rpm), but its performance declined significantly under high humidity (65% RH). The increased surface conductivity of plastic particles under humid conditions disrupted effective charge separation, limiting their effectiveness in uncontrolled environments.

In summary, density separation is proposed for outdoor or industrial applications where environmental robustness, low cost, and process stability are essential. Electrostatic separation, while capable of producing high-purity outputs, is more suitable for indoor, humidity-controlled facilities. A hybrid recycling approach combining both techniques may offer the most effective solution, maximizing efficiency and flexibility in large-scale cable waste recovery systems.

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