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EDDY CURRENT SEPARATION IN NON-FERROUS METAL RECYCLING: MECHANISMS, DESIGN LIMITS, AND INDUSTRIAL SCALE-UP CONSTRAINTS — A CRITICAL REVIEW

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Abstract

Eddy Current Separation (ECS) is widely used in recycling flowsheets to recover non-ferrous metals, particularly from municipal solid waste, electronic waste, and metallurgical residues, where increasing regulatory pressure and circular economy targets demand higher material efficiency. This review critically evaluates the physical principles, equipment design, and operational performance of ECS, with an emphasis on interactions among particle properties (size, shape, conductivity), rotor configuration, and process conditions. While laboratory and pilot studies often report high separation efficiencies (>90% for coarse aluminum fractions), industrial performance is frequently constrained by particle heterogeneity, fines generation (<5 mm), and complex feed compositions, leading to significant losses and misclassification. The review identifies key gaps, including the lack of predictive models for multi-material streams, insufficient integration with upstream comminution and downstream sorting technologies, and limited techno-economic assessments. Particular attention is given to scale-up limitations, rotor wear, energy consumption, and the trade-off between recovery and purity. The analysis highlights that ECS should not be treated as a standalone solution but as a tightly coupled unit within integrated recycling systems. Industrial implications include the need for hybrid separation strategies and improved process control to enhance recovery of fine and complex fractions.

Keywords: Eddy current separation; non-ferrous metals; recycling; particle size effects; separation efficiency; circular economy.

Highlights

- ECS efficiency drops sharply for particles below 5 mm, limiting recovery of fines
- Industrial feeds show lower performance than lab results due to heterogeneity
- Rotor design and speed strongly control separation trajectory and selectivity
- ECS must be integrated with upstream and downstream units for optimal recovery.

Graphical abstract

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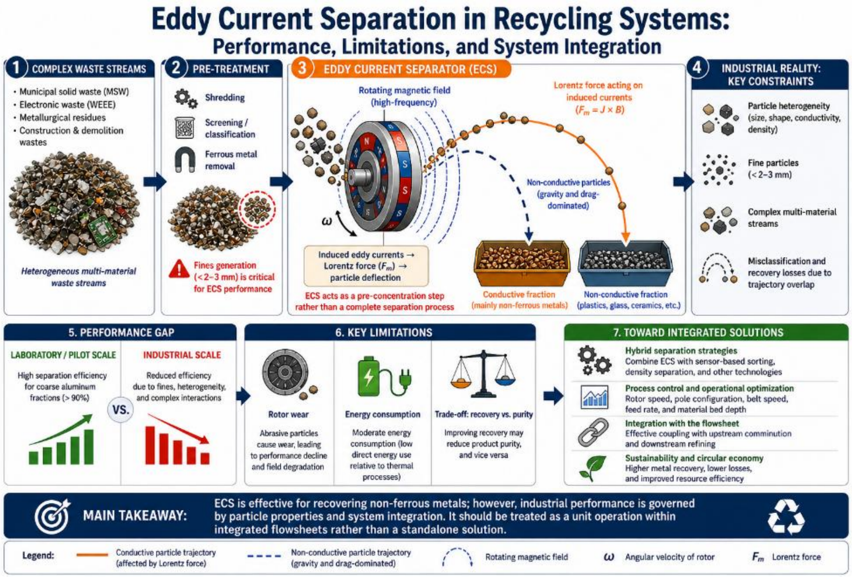

1. Introduction

The recycling of non-ferrous metals has expanded rapidly over the last two decades, driven by resource scarcity, energy constraints, and policies. Secondary production already supplies a major part of global aluminum and copper demand, with energy savings of up to ~95% for aluminum and ~80% for copper (Padamata et al., 2021; Loibl & Espinoza, 2021). This shift benefits the environment and economy, reducing dependence on volatile ore markets and enabling decentralized processing (Pereira & Santos, 2025; Zhu et al., 2025). However, increasing recycling requires efficient upgrading of complex waste streams.

Within this context, eddy current separation (ECS) has become a core technology for the recovery of non-ferrous metals. ECS exploits differences in electrical conductivity to separate metals such as aluminum, copper, and light alloys from non-metallic matrices. Industrial systems typically operate with rotor speeds between 2,000 and 4,000 rpm and magnetic field frequencies above 1 kHz, generating repulsive forces sufficient to displace conductive particles along distinct trajectories (Ye et al., 2020; Panainte & Vădan, 2020). ECS is widely used in aluminum scrap processing, end-of-life vehicles, and electronic waste recycling, where recovery efficiencies can exceed 80–95% for coarse particles (>10 mm) under optimized conditions (Huang et al., 2021; Nagel et al., 2020).

The relevance of ECS increases further in complex secondary streams such as waste electrical and electronic equipment (WEEE) and spent batteries. These materials contain multi-metal assemblies, laminated structures, and fine particles, often with high economic value but difficult physical separability. Typical WEEE streams may contain 10–30 wt.% metals,

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Pages: 1-55

including copper, aluminum, and critical elements, while lithium-ion battery waste introduces additional challenges related to particle size (<5 mm) and composite phases (Agbim et al., 2024; Mishra et al., 2024). Although ECS is routinely used as a pre-concentration step, its performance declines significantly for fine and composite particles, necessitating integration with other separation technologies (Chicardi et al., 2025; Gulliani et al., 2023).

Conventional separation methods have limitations. Magnetic separation only works with ferromagnetic phases and cannot recover non-ferrous metals. Density-based methods are less effective with small density differences or irregular particles. ECS offers a reagent-free, continuous solution, but its selectivity depends on particle size, conductivity, and feed conditions. Efficiency drops sharply below ~2–3 mm in particle size due to reduced induced currents and increased drag, creating a major bottleneck.

Despite extensive ECS research, gaps persist. Most studies focus on lab systems or simple materials, with limited validation at an industrial scale. Performance metrics are inconsistent, hindering cross-study comparison. Integration with advanced modeling, process optimization, and techno-economic analysis remains limited, particularly for emerging applications such as critical metal recovery.

This review critically analyzes eddy current separation from 2010 to 2026, focusing on its physical principles, design parameters, industrial uses, and performance limits, especially in modern recycling. It highlights fine-particle separation, hybrid integration, and digital strategies. Following the PRISMA 2020 framework, the review ensures transparency and reproducibility in literature selection and analysis.

By consolidating experimental, modeling, and industrial data, this work aims to identify realistic performance boundaries and define a research agenda focused on scale-up, standardization, and integration with circular economy systems (Paranjape & Yadav, 2023; Rao et al., 2020; Toro et al., 2023).

2. Methodology

This review adopted a structured, reproducible PRISMA 2020-informed methodology to improve transparency and traceability in the selection, classification, and critical interpretation of the literature on eddy current separation (ECS) (Page et al., 2021). Rather than serving as a purely descriptive survey, the review was designed as a critical synthesis of evidence focused on the physical limitations, industrial applicability, and scale-up constraints of ECS systems.

JIRRS
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The literature search covered the period from 2010 to 2026 and was conducted using the Scopus, Web of Science, and ScienceDirect databases. The search strategy combined terms associated with ECS physics, recycling applications, and industrial processing. Representative search strings included combinations of: "eddy current separation", "ECS", "non-ferrous metal recovery", "WEEE recycling", "aluminum scrap", "bottom ash", "battery recycling", "sensor-based sorting", "magnetic rotor", and "conductive particle separation". Boolean operators (AND/OR) were used to refine the searches according to database-specific syntax. Only documents published in English were considered.

The database search strategy was structured to maximize retrieval consistency and reduce omission of relevant ECS studies across different application domains. Table 1 summarizes the representative search strings, database coverage, time window, and filtering criteria adopted during the literature selection process.

Table 1. Search strategy and database configuration

Database	Representative search string	Period	Filters
Scopus	("eddy current separation" OR ECS) AND recycling	2010–2026	English, peer-reviewed
Web of Science	("eddy current separation" OR ECS) AND ("non-ferrous recovery" OR recycling)	2010–2026	English articles and proceedings
ScienceDirect	"eddy current separation" AND recycling AND metals	2010–2026	Engineering and materials science

Boolean operators, keyword combinations, and database-specific syntax were adjusted to align with each platform's indexing structure to maximize retrieval consistency and reduce duplication.

The review included peer-reviewed journal articles, conference papers, technical reports, and selected review papers that are directly relevant to ECS mechanisms or industrial implementation. Searches were finalized in January 2026. Studies were retained if they reported quantitative or mechanistic information on ECS performance, including recovery, grade, separation efficiency, throughput, rotor speed, magnetic field intensity, particle size, or separator configuration.

The selection workflow is summarized in Figure 1 and follows the PRISMA sequence of identification, screening, eligibility assessment, and final inclusion.

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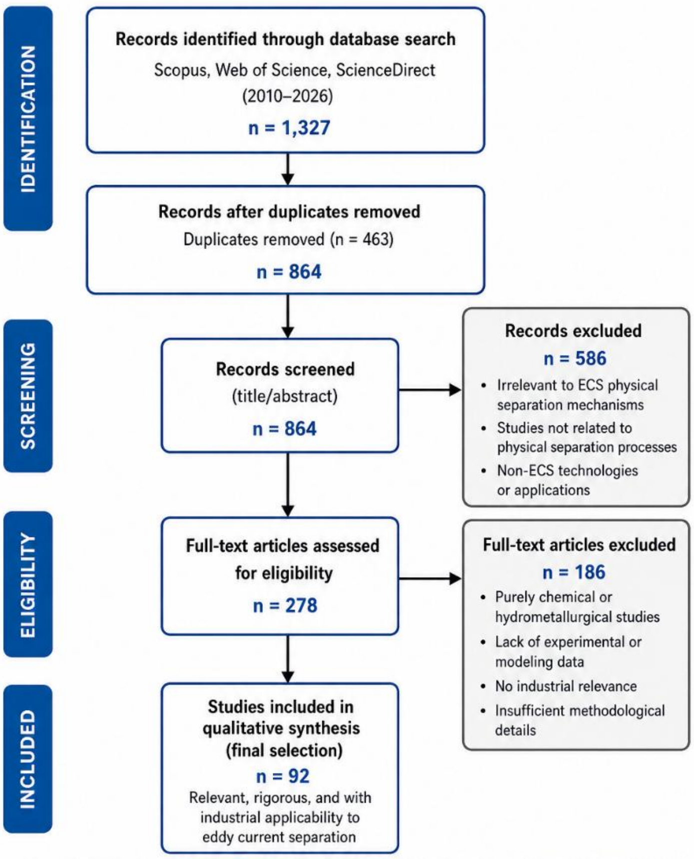

Figure 1. PRISMA 2020 flow diagram for literature selection applied to eddy current separation studies. Adapted from Page et al. (2021).

The initial database search identified 1,327 records. After removal of 463 duplicate entries, 864 records remained for title and abstract screening. Subsequently, 586 records were excluded because they were unrelated to ECS, lacked quantitative or mechanistic information, or focused exclusively on downstream metallurgical processing without physical separation relevance. The remaining 278 full-text articles were assessed for eligibility. Of these, 186 studies were excluded due to insufficient operational detail, lack of experimental validation, absence of ECS-specific analysis, or limited industrial applicability. A final dataset of 92 studies was retained for qualitative synthesis and comparative analysis.

The inclusion criteria were defined to ensure that the review remained focused on ECS as a physical separation technology and on its industrial relevance. Studies were included if they addressed at least one of the following aspects: (i) ECS mechanisms, electromagnetic induction, or particle dynamics; (ii) separator design, rotor configuration, or operational parameters; (iii) ECS application to WEEE, aluminum scrap, slags, batteries, bottom ash, or related secondary materials; (iv) integration of ECS with sensor-based sorting, machine vision,

JIRRS
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density separation, or hybrid flowsheets; or (v) quantitative performance indicators such as recovery, purity, throughput, or energy consumption (Boelens et al., 2025; Chicardi et al., 2025; Mishra et al., 2024).

Studies were excluded if they focused exclusively on hydrometallurgical or pyrometallurgical extraction without a preceding or integrated physical separation stage, lacked experimental or modeling validation, did not provide operationally relevant information, or were unrelated to ECS-based processing. Purely chemical leaching, adsorption, flotation, or bioleaching studies without direct ECS integration were therefore excluded from the final synthesis (Chakraborty et al., 2022; Gulliani et al., 2023; Rao et al., 2020).

To improve evidentiary consistency, the selected studies were additionally classified according to experimental scale, feed complexity, reporting completeness, and level of industrial validation. The literature was grouped into laboratory-scale, pilot-scale, industrial, simulation-based, review, and hybrid experimental–modeling studies. Reporting quality was evaluated based on the availability of key ECS parameters, including particle-size distribution, rotor speed, magnetic field intensity, belt speed, throughput, recovery, purity, and energy consumption. Studies lacking sufficient operational detail were retained only when they provided relevant mechanistic or conceptual contributions.

Because ECS performance is strongly dependent on feed heterogeneity, particle morphology, separator configuration, and operating conditions, quantitative comparisons were interpreted cautiously. Whenever possible, results were normalized using comparable operational metrics, including particle-size range, rotor frequency, recovery efficiency, and throughput. However, the significant variability in reporting standards and experimental methodologies prevented formal meta-analysis. Consequently, the numerical ranges presented throughout this review should be interpreted as indicative operational windows rather than universally transferable performance values.

The final dataset was analyzed using a comparative and critical framework rather than a purely descriptive approach. Studies were systematically organized into five analytical categories: (i) physical principles, (ii) equipment design, (iii) operational parameters, (iv) industrial applications, and (v) technical limitations and scale-up constraints. Particular attention was given to discrepancies between laboratory and industrial performance, fine-particle limitations, feed heterogeneity, and the integration of ECS within hybrid recycling systems.

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Pages: 1-55

Methodological limitations were also considered explicitly. These include the predominance of laboratory-scale studies, underreporting of unsuccessful industrial implementations, variability in performance definitions, and inconsistent reporting of operational parameters. In addition, the screening and study classification procedures were conducted by a single reviewer, which may introduce selection bias and represents an inherent limitation of the review methodology.

The resulting dataset provides a structured basis for critically analyzing the physical mechanisms, industrial performance, and scale-up limitations governing eddy current separation systems.

3. Physical Principles of Eddy Current Separation

Eddy current separation (ECS) is governed by electromagnetic induction, force generation, and particle dynamics under high-frequency alternating magnetic fields. While the underlying physics is well established, its translation into predictive industrial models remains limited. This section consolidates the fundamental mechanisms and highlights the gap between theoretical descriptions and operational performance.

3.1. Faraday's law, Lenz's law and electromagnetic induction

ECS relies on Faraday's law, where changing magnetic fields induce eddy currents in conductive particles. These currents create secondary magnetic fields opposing the original, per Lenz's law (Ye et al., 2020; Merahi et al., 2020).

In industrial ECS units, rotating magnetic rotors produce field frequencies typically ranging from 500 Hz to 5 kHz, depending on rotor speed and pole configuration. The induced current density in a particle is proportional to:

- Electrical conductivity σ(S/m)
- Magnetic field variation $\frac{dB}{dt}$
- Particle geometry and exposure time

Materials with high conductivity, such as aluminum (~3.5–3.8 × 10^7 S/m) and copper (~5.8 × 10^7 S/m), generate stronger eddy currents and respond more effectively to the magnetic field (Lv et al., 2023).

However, induction efficiency decreases rapidly for small particles because of reduced interaction volume and shorter residence time in the magnetic field. This effect becomes critical below ~2–3 mm, where induced currents are insufficient to produce measurable displacement.

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3.2. Magnetic repulsive force, conductivity and density effects

Induced eddy currents interact with the magnetic field, creating a Lorentz force that causes particle separation.

In simplified form, the repulsive force Fcan be expressed as:

$$F_m \propto \sigma \cdot B^2 \cdot V$$

where:

- σ= electrical conductivity
- B= magnetic flux density (typically 0.5–1.5 T at rotor surface)
- V= particle volume

This relationship explains why ECS performance is strongly dependent on both conductivity and particle size (Bendimerad et al., 2024; Bin et al., 2024).

However, separation is not governed by force alone. The particle's mass introduces inertia, resulting in a force-to-mass ratio:

$$\frac{F}{m} \propto \frac{\sigma B^2}{\rho}$$

Where $\rho$is density. As a result:

- Aluminum (low density, high conductivity) → high displacement
- Copper (high density, high conductivity) → moderate displacement
- Stainless steel (low conductivity) → minimal response

This explains the difficulty of separating metals with similar conductivity-to-density ratios, such as Cu vs Al mixtures, especially in fine fractions.

Particle motion in ECS systems results from a balance of forces like electromagnetic repulsion (Lorentz force), gravity, drag, and friction at the conveyor. This coupled force–motion system, not just magnetic response, determines separation efficiency.

For particles over 10 mm, inertial effects dominate, and trajectories follow ballistic paths. The electromagnetic force can then cause spatial separation and high selectivity. Conversely, particles smaller than 5 mm are affected by drag and exhibit less effective induction, leading to shorter flights, overlapping paths, and more errors. This shift from inertia to drag limits fine particle recovery (Bai et al., 2023; Shan et al., 2024).

Particle shape adds complexity by affecting eddy current distribution and aerodynamic response. Flat or elongated particles have larger surface areas perpendicular to the magnetic field, increasing induced current and electromagnetic repulsion. For example, flake-like

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aluminum particles generate stronger induced currents and better separation. Conversely, irregular or composite particles create uneven current distributions and unstable trajectories, lowering separation efficiency.

Experimental and numerical studies show particle shape can alter separation efficiency by 10–30%, depending on rotor design, belt speed, and particle size (Huang et al., 2024). These effects interact with operating conditions, emphasizing ECS separation as a coupled, nonlinear transport–force problem, not just a magnetic process.

3.3. Mathematical and numerical modeling

Mathematical modeling of ECS couples electromagnetic, mechanical, and fluid phenomena. Simplified models describe induced current and forces but often omit particle interactions and industrial complexities.

Key dimensionless parameters include the magnetic Reynolds number:

$$Re_m = \mu\sigma vL$$

where:

- μ= magnetic permeability
- σ= conductivity
- v= particle velocity
- L= characteristic length

For typical ECS operating conditions, the skin depth is often much smaller than the characteristic particle size for highly conductive metals. This justifies quasi-static approximations in many models.

Another critical parameter is the skin depth, denoted by δ, which defines the penetration depth of the alternating magnetic field into a conductive material.:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}}$$

where $\delta$is the skin depth, $\omega$is the angular frequency of the magnetic field, $\mu$is the magnetic permeability of the material, Sigma is the electrical conductivity.

At frequencies above ~1 kHz, the skin depth in aluminum is on the order of 1–5 mm, so only the outer layer contributes to current generation. This limits efficiency for larger particles and partially explains performance saturation at high frequencies.

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Pages: 1-55

Numerical approaches like FEM and coupled simulations enhance prediction accuracy (Bettache et al., 2024; Ouili et al., 2023; Zyazev et al., 2023). Recent studies use machine learning to predict particle paths and optimize conditions (Zhang et al., 2024). However, these models are rarely validated with full-scale industrial data.

Table 2 summarizes the key physical parameters governing eddy current separation. These variables control induced currents, magnetic forces, and particle trajectories.

Table 2. Key physical parameters governing eddy current separation and their influence on particle dynamics. Adapted from Ye et al. (2020), Bin et al. (2024), and Hader et al. (2024).

Parameter	Typical Range	Influence on Separation
Electrical conductivity (σ)	10^5–10^7 S/m	Higher σ → stronger eddy currents
Magnetic flux density (B)	0.5–1.5 T	Higher B → higher force
Rotor frequency	500–5000 Hz	Controls induction intensity
Particle size	1–100 mm	<3 mm → strong efficiency loss
Density (ρ)	2–8 g/cm³	Higher ρ → lower displacement
Skin depth (δ)	1–10 mm	Limits current penetration

Table 2 shows that ECS performance depends on the coupled effects of conductivity, particle size, and frequency. Efficiency decreases sharply for particles below 3–5 mm, highlighting a major limitation of the process.

Eddy current separators (ECS) use electromagnetic induction and particle dynamics for separation. Conductive particles in a changing magnetic field develop eddy currents that oppose flux changes (Lenz's law). These currents produce a repulsive force, altering their paths versus non-conductive materials. Figure 2 illustrates this process, linking eddy currents, force, and movement.

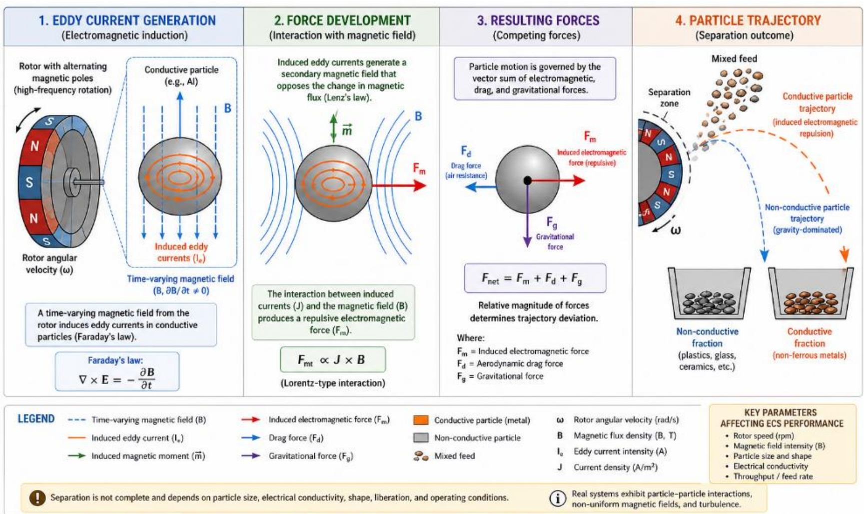

Figure 2. Schematic representation of eddy current generation, force development, and particle trajectory in ECS systems. Adapted from Ye et al. (2020) and Bin et al. (2024).

JIRRS Journal International Review of Research Studies
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Pages: 1-55

Figure 2 illustrates the coupling between electromagnetic induction and particle dynamics. The separation outcome results from the interaction between induced currents, magnetic forces, and competing drag and gravitational forces.

Critical assessment

Although ECS principles are well established, applying them industrially is limited. Most models are simplified, assuming isolated particles, uniform magnetic fields, and steady conditions, which don't reflect real system complexities.

Industrial ECS units use polydisperse feeds, with particle size, shape, and composition varying continuously. Particle interactions, moisture content, and feed thickness affect flow and cohesion, while non-uniform magnetic fields result from design and tolerances, creating a dynamic, heterogeneous separation environment.

Model predictions often overestimate separation efficiency, especially for fine and composite particles. The gap between controlled and industrial settings reduces their predictive accuracy and limits scalability and process optimization. A major gap remains in validated multiphysics frameworks that combine electromagnetic, mechanical, and fluid dynamic effects.

The translation of these physical principles into practical systems is examined in Section 4, with emphasis on equipment design and operational parameters that define real ECS performance.

4. Design and Operational Parameters

The performance of eddy current separation (ECS) is not dictated by physics alone. Equipment design and operating conditions control how effectively electromagnetic forces translate into particle displacement. In industrial systems, small changes in rotor configuration, belt speed, or feed conditions can shift recovery and grade by more than 20–40%. This section critically examines the key design variables and their practical limits.

4.1. Magnetic rotor, poles, field intensity and Halbach arrangements

The magnetic rotor, central to ECS performance, generates the magnetic field that induces eddy currents in conductive particles. Its design depends on three parameters: rotational speed, magnetic poles, and field strength.

Industrial rotors usually operate at 2,000–4,000 rpm, with magnetic field frequencies between about 500 and 5,000 Hz depending on pole setup. Increasing poles raises frequency

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Pages: 1-55

but reduces electromagnetic penetration. This creates a trade-off: higher frequencies improve induction in fine particles, while lower frequencies allow deeper penetration for coarse particles. Thus, one rotor design can't be optimal for all particle sizes.

Magnetic field intensity at the rotor surface generally ranges from 0.5 to 1.5 T, depending on magnet material and configuration, with NdFeB magnets being the industrial standard due to their high remanence and stability (Bin et al., 2021; Yuan et al., 2023). Recent developments have focused on optimizing field distribution rather than simply increasing intensity.

Advanced rotor designs use Halbach arrays to concentrate magnetic fields on the active side, reducing losses on the opposite. This can boost effective field strength by about 20–40% without extra power, enhancing energy efficiency and particle acceleration (Shan et al., 2025d; Shan et al., 2026).

Despite these advances, most industrial ECS systems still rely on fixed-frequency rotors. This limits operational flexibility when processing heterogeneous feeds, where optimal frequency varies with particle size and composition. Consequently, performance is often a compromise rather than a fully optimized condition across the entire material spectrum

4.2. Separator structure and magnetic roller arrangement

Separator configuration defines how particles interact with the magnetic field and strongly influences separation efficiency. The most common industrial designs include drum-type ECS with horizontal rotors, vertical ECS systems, and barrier-type configurations (BECS). Among these, drum-type separators dominate industrial applications due to their mechanical simplicity, robustness, and ability to handle high throughput.

Recent studies show alternative configurations, like vertical ECS systems, can improve selectivity by changing magnetic force direction, aiding metal discrimination, such as aluminum and copper. While 10–25% efficiency gains have been reported (Shan et al., 2024), these gains are not always achieved in industry due to feed variability and throughput constraints.

Magnetic roller design influences field distribution and particle interaction. Parameters such as air gap, sleeve thickness, and rotor eccentricity affect the magnetic field strength. Thicker sleeves can decrease field intensity by 15–30%, while a smaller air gap boosts magnetic force but raises wear and maintenance (Park & Ahn, 2025). These trade-offs are key in design.

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Pages: 1-55

In industrial installations, optimization of magnetic parameters is often constrained by mechanical and operational considerations. As a result, ECS systems are rarely operated at theoretically optimal conditions, reinforcing the importance of integrated design approaches that balance electromagnetic performance with mechanical reliability.

4.3. Belt speed, feed system and rotational speed

Operational parameters, especially belt speed, govern particle residence time and magnetic exposure. Conveyor speeds vary from 1 to 3 m/s. Lower speeds increase interaction time and trajectory deviation but limit throughput; higher speeds improve throughput but reduce separation efficiency due to shorter exposure (Assidiqqi & Dhelika, 2024).

Rotor speed should be considered with belt speed. Effective separation relies on synchronizing magnetic field frequency, particle velocity, and residence time. Mismatched parameters cause significant performance losses, with recovery dropping 15–35% even within nominal ranges (Fatra & Dhelika, 2024). This shows ECS systems have a narrow operating window.

The feed system is crucial, with feed thickness kept at 1–3 particle layers to expose particles to the magnetic field. Poor dispersion or deep beds cause particle shielding, reducing electromagnetic force. Moisture worsens this, as 2–5 wt% moisture increases cohesion, changes flow, and decreases separation by 10–20% (Kia & Leiding, 2025).

4.4. Particle size and granulometric limitations

Particle size limits ECS performance; stable operation typically occurs in the 5–50 mm range, where currents deflect particles effectively. Under this, performance drops, with >10 mm particles reaching over 90% recovery for aluminum, 5–10 mm range at 70–90%, and <5 mm below 60%. For <2–3 mm, separation often falls below 30–40% (Bin et al., 2022; Yi et al., 2022).

This behavior is governed by physical constraints. Smaller particles produce weaker eddy currents due to less conductive volume, and drag and turbulence dominate their motion. Consequently, particle paths overlap, reducing selectivity and predictability. Additionally, fine particles in streams such as WEEE and battery waste often form composites or agglomerates, with varying conductivity and density, complicating separation.

Despite research, efficient separation below 2–3 mm remains unsolved. Solutions such as high-frequency ECS, multi-stage separation, and hybrid sensors offer localized

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Pages: 1-55

improvements but often increase costs and lack consistent industrial validation (Shan et al., 2025a).

Table 3 summarizes the main design and operational parameters of eddy current separators. These variables directly influence magnetic field generation, particle acceleration, and overall separation efficiency.

Table 3. Design and operational parameters of eddy current separators and their influence on performance. Adapted from Bin et al. (2021), Yuan et al. (2023), and Shan et al. (2025c).

Parameter	Typical Range	Impact on Performance
Rotor speed	2,000–4,000 rpm	Controls field frequency
Magnetic field intensity	0.5–1.5 T	Determines force magnitude
Number of poles	8–48	Affects frequency and penetration
Belt speed	1–3 m/s	Controls residence time
Feed thickness	1–3 layers	Affects exposure to field
Particle size	1–100 mm	<5 mm reduces efficiency
Moisture content	0–5 wt%	Reduces separation efficiency
Air gap	5–20 mm	Influences effective field

Table 3 indicates that rotor configuration, belt speed, and particle size are the dominant factors controlling performance. Optimal operation typically requires high rotor frequencies and controlled feed conditions, while efficiency decreases significantly for fine particles (<5 mm).

Figure 3 shows how rotor configuration, belt speed, and particle size interact to define ECS performance, highlighting the narrow conditions needed for high recovery and grade.

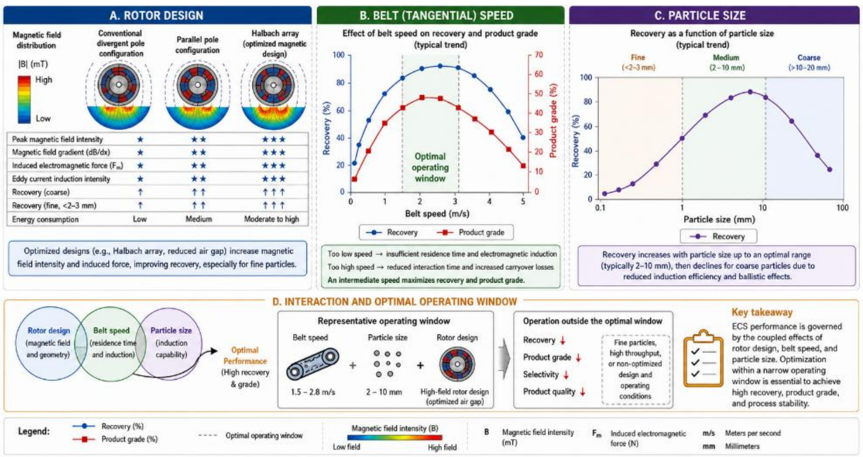

Figure 3. Influence of rotor design, belt speed, and particle size on ECS performance. Adapted from Bin et al. (2022), Shan et al. (2024), and Kia & Leiding (2025).

Figure 3 summarizes the interaction between design and operational parameters. Optimal performance is achieved within a narrow operating window. Outside this range,

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Pages: 1-55

recovery and grade decline rapidly, particularly for fine particles and high-throughput conditions.

Critical assessment

Most studies optimize ECS parameters in isolation, overlooking the strong coupling between variables. For example, increasing rotor speed without adjusting belt speed or feed conditions may reduce, rather than improve, separation efficiency.

In industrial systems, operation rarely occurs under optimal conditions due to variable feed composition, equipment wear, throughput constraints, and energy considerations. As a result, laboratory-reported efficiencies often exceed industrial performance by 20–40%.

The most critical unresolved issue remains the granulometric limitation below ~2–5 mm, where separation efficiency declines sharply. This constraint directly impacts recovery in modern recycling streams, particularly in WEEE and battery processing, where fine particles represent an increasing fraction of the feed.

The implications of these design and operational constraints are discussed in Section 5, with emphasis on industrial applications and real process performance.

5. Industrial Applications

Eddy current separation (ECS) is commonly used in recycling and metallurgical industries, processing large volumes (5–50 t/h) with low energy (≈ 0.5–2.5 kWh/t). Its effectiveness depends on feed quality and preparation. This section reviews key applications, focusing on recovery, grade, and process integration.

5.1. WEEE and printed circuit boards

Waste electrical and electronic equipment (WEEE) is the most established application of ECS. After shredding and magnetic separation, ECS is used to recover non-ferrous metals—primarily aluminum and copper—from mixed streams.

Typical performance in industrial and semi-industrial systems includes aluminum recovery of 80–95%, copper recovery of 60–85%, and product purity ranging from 70 to 95%, depending on particle size and degree of liberation. ECS is most effective for particles between ~5 and 30 mm, which represent the dominant fraction after shredding (Huang et al., 2021; de Buzin et al., 2021).

JIRRS
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Pages: 1-55

However, WEEE streams present several critical challenges, including composite particles (e.g., metal–plastic laminates), fine fractions (<5 mm) with low separation efficiency, and pronounced material heterogeneity with overlapping conductivity and density ranges.

Recent studies indicate that combining ECS with sensor-based sorting technologies—such as optical systems, XRT, or machine vision—can improve metal purity by approximately 10–25%, although this comes with increased capital costs (Agbim et al., 2024; Wędrychowicz et al., 2023).

5.2. Aluminum recycling and aluminum scrap

ECS plays a central role in aluminum scrap processing, particularly in post-consumer streams such as packaging, automotive scrap, and mixed metal residues. Industrial systems typically achieve recovery above 90% for particles larger than ~10 mm, with purity ranging from 85 to 98%, depending on feed contamination. Throughput can reach up to 50 t/h per line in large-scale facilities.

A key advantage of ECS in aluminum recycling is its ability to replace manual or density-based sorting, reducing labor costs and improving process consistency (Pereira, 2025a; Pereira & Santos, 2025).

However, important limitations remain, including inefficient separation of thin foils and laminated materials, as well as reduced performance for fine fractions (<5 mm). To overcome these constraints, ECS is commonly integrated into multi-stage processing circuits, such as magnetic separation → ECS → sensor-based sorting → refining. This integration is essential to meet smelter-grade specifications, particularly in secondary aluminum production (Pereira, 2025b; Pereira, 2026f).

5.3. Batteries and Li-ion/LFP recycling

The rapid growth of lithium-ion battery recycling has introduced new challenges for ECS. Battery waste streams are highly heterogeneous, containing aluminum and copper foils, active materials (Li, Co, Ni, Mn compounds), and polymer separators.

In this context, ECS is primarily applied in the pre-treatment stage, following shredding and thermal or mechanical liberation. Reported performance includes aluminum and copper recovery in the range of 70–90%, with purity typically between 60 and 85%, often limited by contamination from active materials (Bi et al., 2021; Bai et al., 2023).

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Separation efficiency is strongly constrained by fine particle sizes (often <5 mm) and the presence of composite structures, which reduce effective conductivity and lead to unstable particle trajectories. In addition, the increasing presence of low-conductivity coatings and degraded materials further limits eddy current induction.

As a result, ECS alone is insufficient for effective separation in battery recycling. It is typically combined with complementary technologies such as air classification, sieving, and sensor-based sorting to improve selectivity and overall process performance (Li et al., 2024; Staudacher et al., 2024).

5.4. MSWI bottom ash and mineralized residues

Municipal solid waste incineration (MSWI) bottom ash is a complex, mineral-rich stream containing both ferrous and non-ferrous metals. ECS is used to recover aluminum fragments, copper wires and particles, and other non-ferrous metals from this heterogeneous matrix.

Typical industrial performance ranges from 50 to 80% recovery—strongly dependent on particle size—and 60 to 85% purity. Performance is generally lower than in WEEE processing because of mineral adhesion, irregular particle shapes, and oxidized metal surfaces, all of which affect conductivity and particle trajectories.

Advanced configurations incorporating multi-stage ECS and density-based separation can improve recovery by approximately 10–20%, although this comes at the cost of increased process complexity and operational requirements (Adhiwiguna et al., 2025; Mühl et al., 2024).

5.5. Slags and metallurgical residues

ECS is increasingly applied to metallurgical slags, including electric arc furnace (EAF) slag, aluminum salt slag, and non-ferrous smelting residues. In these systems, ECS targets metallic inclusions embedded within a predominantly mineral matrix.

Typical performance is lower than in conventional scrap processing, with recovery ranging from 40 to 85% and purity between 50 and 80%. This reduced efficiency is mainly associated with partial liberation, the high density of surrounding mineral phases, and irregular particle morphology, all of which affect particle trajectories and separation behavior.

In EAF slag processing, ECS is typically integrated with crushing, screening, and magnetic separation stages. Although recovery levels are moderate, the economic benefit lies in reducing metal losses, upgrading material streams, and improving the efficiency of

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

downstream processing (Kurecki et al., 2025; Pereira et al., 2025; Pereira, 2025c; Pereira, 2025d).

5.6. Critical and strategic metals

ECS is not designed for the direct recovery of critical metals such as Li, Ga, or rare earth elements (REEs). Instead, it plays an enabling role by concentrating conductive fractions, removing metallic contaminants, and preparing the feed for downstream hydrometallurgical or pyrometallurgical processes.

In this context, its contribution is indirect but significant. Pre-concentration of metallic fractions can reduce downstream processing costs by approximately 10–30%, while the removal of Al and Cu improves selectivity in leaching circuits (Pereira, 2026e; Pereira, 2026d; Pereira, 2026a; Pereira, 2025l).

Table 4 compiles representative industrial performance ranges of ECS across major application domains, reflecting typical operating windows reported in the literature and the variability associated with feed characteristics and material complexity.

Table 4. Industrial performance of eddy current separation across different applications. Adapted from Huang et al. (2021), Bi et al. (2021), Adhiwiguna et al. (2025), Kurecki et al. (2025), Pereira et al. (2025) and Pereira (2025a).

Application	Particle size (mm)	Recovery (%)	Purity (%)	Key limitation
WEEE	5–30	60–95	70–95	Composite particles
Aluminum scrap	10–50	85–98	85–98	Thin foils
Batteries	1–10	70–90	60–85	Fine fractions
Bottom ash	5–50	50–80	60–85	Mineral adhesion
Slags	5–100	40–85	50–80	Liberation
Critical metals (pre-treatment)	1–50	Indirect	Indirect	Not selective

Table 4 shows that ECS achieves high recovery and purity for coarse, well-liberated metallic fractions, especially in aluminum scrap. Performance declines in complex systems such as WEEE, batteries, and bottom ash because of composite particles and fine fractions. Feed composition and degree of liberation are key constraints on industrial efficiency.

ECS serves as an intermediate step in multi-stage recycling, aiding pre-concentration of non-ferrous metals and enhancing feed quality. Its role varies depending on the material, such as electronic waste, spent batteries, or metallurgical residues. Figure 4 shows industrial setups illustrating ECS integration with other processes.

Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

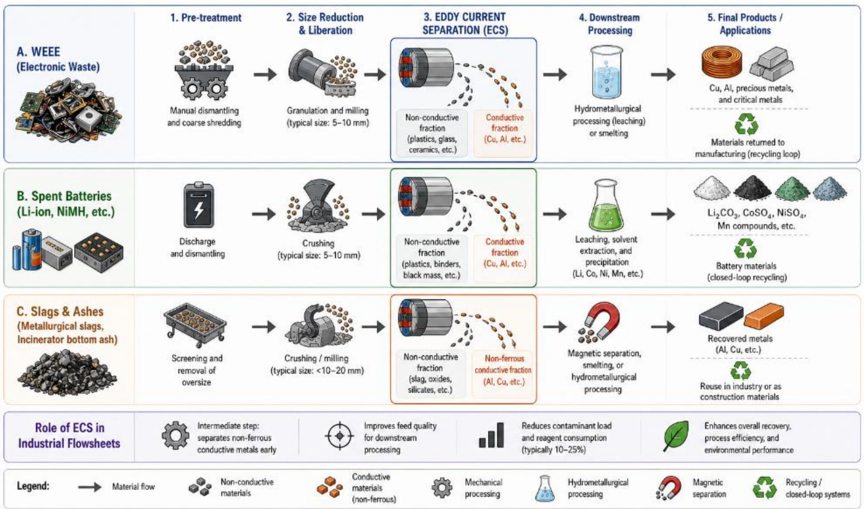

Figure 4. Typical ECS integration in industrial recycling flowsheets (WEEE, batteries, slags). Adapted from Huang et al. (2021), Adhiwiguna et al. (2025), and Pereira (2025a).

Figure 4 illustrates the role of ECS within multi-stage processing routes. In all cases, ECS operates as an intermediate step rather than a standalone solution. Its effectiveness depends on upstream liberation and downstream purification.

Critical assessment

ECS is widely implemented but rarely sufficient as a standalone technology. Industrial performance typically reflects a trade-off between recovery and purity: maximizing recovery often increases contamination, while achieving high purity reduces yield.

Integration with complementary technologies has become standard, with hybrid systems that combine ECS, magnetic separation, density separation, and sensor sorting consistently outperforming standalone units in efficiency and quality.

Despite these advances, three persistent limitations remain: reduced performance for fine particles (<2–5 mm), limited selectivity for materials with similar conductivity, and strong sensitivity to feed variability and moisture. These constraints define the practical boundary of ECS applicability in industrial systems.

Future developments must address these limitations to remain effective in increasingly complex recycling streams. Section 6 analyzes how ECS performance is quantified and optimized, including empirical models, CFD-based simulations, and machine learning approaches.

Although ECS is used in various recycling streams, its performance varies significantly based on feed composition, particle shape, liberation, and size distribution. Therefore,

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

conclusions from one material cannot be generalized to others without considering boundary conditions and process limits (Table 5).

Table 5. Boundary conditions and ECS applicability by feed stream

Feed stream	ECS suitability	Main limitation	Recommended complementary technology
Aluminum scrap	High	Thin foils and laminated particles	Sensor-based sorting
WEEE	Moderate	Composite and heterogeneous particles	XRT + machine vision
LIB waste	Low–moderate	Fine particles and conductive coatings	Air classification
Bottom ash	Moderate	Mineral adhesion and irregular morphology	Density separation
Slags	Moderate	Partial liberation and high mineral content	Crushing and screening

Table 5 highlights that the applicability of ECS is strongly dependent on feed characteristics and operating conditions. High performance is generally associated with coarse, well-liberated conductive particles, whereas fine fractions, composite materials, and mineralized residues significantly reduce selectivity and process stability.

The table also demonstrates that ECS rarely functions as a standalone solution in complex recycling systems. Instead, its industrial implementation increasingly depends on integration with complementary separation technologies capable of compensating for the intrinsic physical limitations of electromagnetic separation.

These boundary conditions directly influence how ECS performance is quantified and optimized under industrial conditions. Section 6 therefore examines the principal performance metrics, optimization strategies, and predictive approaches used to evaluate ECS systems.

6. Performance Metrics and Process Optimization

Quantifying ECS performance is complex due to non-standardized metrics measured under varying conditions. Most studies report recovery and grade, but fewer include throughput or energy use, making technology comparison and scaling challenging.

6.1. Recovery, grade, and separation efficiency

ECS performance is typically evaluated using three primary indicators: recovery (%), grade (%), and separation efficiency. Recovery represents the fraction of target metal recovered relative to its initial content, while grade reflects the purity of the recovered fraction.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

In industrial systems, recovery is usually 60–95% for aluminum and 50–85% for copper, depending on particle size and liberation. Grade values range from 70 to 98%, with higher purity often decreasing recovery (Huang et al., 2021; Bin et al., 2022).

Separation efficiency combines recovery and grade into a single metric, but its definition varies. Some studies use mass-based formulas, while others include trajectory- or force-based criteria, making comparisons difficult (Shan et al., 2025a).

Throughput is key in industrial applications, with ECS units typically operating at 5-50 t/h. Performance declines at higher feed rates due to particle shielding and reduced residence time. However, specific energy consumption remains low, at 0.5–2.5 kWh/t, a major benefit for large-scale recycling.

Table 6 summarizes the main performance metrics used to evaluate ECS, highlighting both their relevance and the lack of standardization across studies.

Table 6. Typical performance metrics used in eddy current separation evaluation. Adapted from Huang et al. (2021), Bin et al. (2022), and Shan et al. (2025a).

Metric	Typical Range	Limitation
Recovery (%)	50–95	Sensitive to particle size
Grade (%)	60–98	Trade-off with recovery
Separation efficiency	50–90	Not standardized
Throughput (t/h)	5–50	Reduces efficiency at high load
Energy (kWh/t)	0.5–2.5	Often not reported

Table 6 shows that performance evaluation is highly dependent on the selected metric. Recovery and grade often exhibit a trade-off, while separation efficiency lacks a unified definition. In addition, energy consumption is inconsistently reported, limiting comparative analysis.

6.2. Recovery–purity–throughput trade-offs

ECS optimization is inherently multi-objective. Maximizing metal recovery often increases contamination in the conductive fraction, whereas maximizing purity reduces overall yield and may increase losses of valuable metals.

In industrial practice, separator tuning therefore reflects economic rather than purely physical optimization, including downstream smelter specifications, contamination-related penalty costs, throughput constraints, and energy consumption.

This trade-off becomes particularly important in heterogeneous recycling streams such as WEEE, bottom ash, and battery waste, where maximizing recovery often increases the

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

entrainment of non-conductive or composite particles. Conversely, highly selective operating conditions may reduce throughput and increase losses of valuable metals.

Throughput introduces an additional operational constraint. Increasing feed rate generally improves process productivity but reduces particle exposure time to the magnetic field, intensifies particle shielding effects, and decreases trajectory discrimination. As a result, industrial ECS systems frequently operate under compromise conditions rather than under theoretically optimal separation parameters.

The recovery–purity relationship is therefore strongly dependent on feed composition, particle-size distribution, rotor configuration, and separator tuning. In coarse and well-liberated aluminum scrap, high recovery and purity can be achieved simultaneously. However, in fine and heterogeneous streams, increasing recovery often produces a disproportionate decline in concentrate quality.

Consequently, ECS optimization should not be interpreted as a single-parameter maximization problem, but rather as a balance among recovery, purity, throughput, operational stability, and downstream processing requirements.

6.3. Empirical models and force–trajectory correlations

Empirical models are widely used to relate operating parameters to ECS performance by correlating variables such as magnetic field intensity, rotor speed, particle size, and electrical conductivity with particle trajectory and separation distance.

Recent studies confirm that the induced electromagnetic force scales with particle conductivity and volume, but is also strongly influenced by particle shape, orientation, and surface condition (Bin et al., 2024; Bendimerad et al., 2024). As a result, simple correlations often fail to capture the variability observed in real systems.

Trajectory-based models are commonly used to predict separation zones, employing simplified force balances among the induced electromagnetic force, gravity, and aerodynamic drag. While these models provide useful first-order insights, they typically assume spherical particles and uniform magnetic fields.

Such assumptions limit their applicability to industrial conditions, where particles are irregular, composite, and subjected to highly non-uniform fields and complex flow regimes (Lv et al., 2023).

6.4. Analytical and empirical models

JIRRS Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Numerical simulation has become a key tool for ECS optimization, enabling detailed analysis of electromagnetic fields and particle dynamics. Most studies use finite element methods (FEM) to model the magnetic field, coupled with particle motion approaches such as discrete element modeling (DEM).

Typical approaches include electromagnetic field simulation based on Maxwell equations, discrete particle modeling (DEM), and coupled CFD–DEM frameworks to account for airflow and drag effects. These models can predict eddy current distribution, induced force magnitude, and particle trajectories within the separator.

Simulation results indicate that force magnitude can vary by 30–50% within the same separator due to magnetic field heterogeneity (Merahi et al., 2020; Bettache et al., 2024). This highlights the importance of spatial effects and equipment design on separation performance.

However, most models are validated at laboratory scale, and industrial validation remains limited. This creates uncertainty when extrapolating simulation results to large-scale systems and complex, variable feeds (Li et al., 2021; Zhang et al., 2024).

6.5. FEM and coupled CFD–DEM simulation

Machine learning (ML) is increasingly used to optimize ECS by leveraging data-driven relationships between process variables and performance. Unlike physics-based models, ML depends on correlations from datasets.

Typical applications include prediction of recovery and grade, optimization of rotor and belt speeds, and real-time process control. Reported improvements in separation efficiency range from 5–20% when ML is used for parameter tuning (Chen et al., 2021; Bettache et al., 2026). ML is also combined with machine vision systems to enable adaptive sorting based on particle characteristics, which is particularly relevant for complex streams such as WEEE (Kia et al., 2025; Williams et al., 2023).

Despite these advances, two main limitations remain: the scarcity of large, high-quality industrial datasets and the limited interpretability of ML models compared to physics-based approaches.

Optimizing ECS performance requires integrating empirical models, physics-based simulation, and data-driven methods. Their combination enables more robust prediction and system optimization. Figure 5 shows an integrated framework linking these approaches for ECS design and operation.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

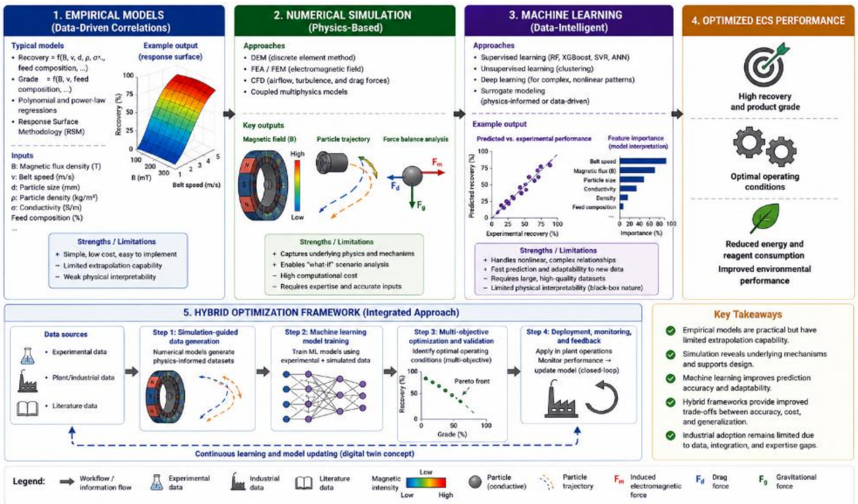

Figure 5. Framework for ECS performance optimization combining empirical models, numerical simulation, and machine learning. Adapted from Bettache et al. (2024), Chen et al. (2021), and Kia et al. (2025).

Figure 5 illustrates the evolution from empirical approaches to hybrid optimization frameworks. While simulation improves physical understanding, machine learning enhances adaptability. The integration of both remains limited in industrial practice.

Critical assessment

ECS performance evaluation remains limited by a lack of standardization. While recovery and grade are commonly reported, key aspects are often inconsistent or missing. Definitions of separation efficiency vary across studies, energy consumption is frequently not quantified, and the influence of throughput is rarely addressed. This lack of uniformity prevents meaningful comparison between results.

A further limitation is the gap between laboratory and industrial data. Many studies report optimized performance under controlled conditions, without accounting for feed variability, moisture, and particle–particle interactions. As a result, industrial performance is often 20–40% lower than laboratory values.

Optimization approaches are also fragmented. Empirical correlations, numerical simulations, and machine learning methods are typically developed in isolation, with limited integration into unified predictive frameworks. This restricts the ability to optimize ECS systems under realistic operating conditions.

Section 7 examines the fundamental limitations and technical challenges that constrain ECS performance across different applications.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

7. Limitations and Technical Challenges

Despite its maturity, ECS is constrained by fundamental physical limitations and practical operational issues. These constraints define the boundaries of applicability and explain why ECS is rarely used as a standalone solution in complex recycling systems. The limitations discussed here are not independent; they interact and often amplify each other under industrial conditions.

7.1. Fine particles and low separation efficiency

Particle size remains the most critical limitation of ECS. As particle diameter decreases, the induced eddy current and resulting electromagnetic force drop sharply due to reduced conductive volume and the increasing influence of drag and gravitational forces.

Experimental data consistently show that separation efficiency remains high (>80%) for particles above ~10 mm, declines significantly in the 5–10 mm range, becomes unstable below ~5 mm, and can drop to <30–40% for particles smaller than ~2–3 mm (Bin et al., 2022; Huang et al., 2021; Shan et al., 2025a).

At small particle sizes, the skin depth becomes comparable to or larger than the particle dimension, limiting effective current induction. In addition, fine particles exhibit erratic trajectories due to turbulence, air drag, and particle–particle interactions (Louahadj et al., 2024).

This limitation is particularly critical in modern recycling streams. In WEEE and battery processing, fine fractions can represent 30–60% of the total mass, meaning that ECS does not efficiently recover a substantial portion of valuable metals.

7.2. Particle interaction and mixed-feed effects

Most ECS models assume isolated particles, whereas industrial systems process dense, heterogeneous feeds. Under these conditions, particle–particle interactions become significant and often dominate separation behavior.

Key interaction mechanisms include shielding effects—where upper particles reduce the magnetic field exposure of lower particles—collision-induced trajectory deviations, and agglomeration driven by fines and moisture. Together, these effects can reduce recovery by 10–30% relative to idealized conditions (Shan et al., 2024).

Mixed feeds further complicate separation. Particles with similar electrical conductivity but different densities—or vice versa—can follow overlapping trajectories, limiting selectivity.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

For example, aluminum and magnesium alloys may not be effectively separated despite differences in conductivity (Ali, 2024).

In battery recycling streams, interactions between metallic foils and active material powders lead to highly variable and often unpredictable separation behavior, reinforcing the need for pre-conditioning and integrated process control (Bai et al., 2023; Staudacher et al., 2024).

7.3. Composite, laminated and multilayer materials

ECS is limited for composite materials like aluminum–plastic laminates, PCBs, and battery electrodes, where non-uniform conductivity reduces eddy current, causes irregular forces, and unpredictable particle paths.

As a result, metal recovery from laminated or composite materials can be 30–50% lower than from fully liberated particles (Kaiser, 2020; Shukla et al., 2022). Effective separation, therefore, depends on prior delamination or pre-treatment. However, these steps increase process complexity and cost, and mechanical liberation is often incomplete, particularly for thin or flexible materials.

Recent approaches combine ECS with thermal or chemical pre-treatment to improve liberation, but these strategies introduce additional environmental and economic trade-offs (Shoaie & Bazargan, 2025).

7.4. Temperature, moisture, and operational instability

ECS performance is highly sensitive to operating conditions, particularly moisture and temperature. Moisture affects separation by increasing particle cohesion and agglomeration, reducing mobility, and altering surface conductivity. Even low moisture levels (≈2–5 wt%) can reduce separation efficiency by 10–20%, especially for fine particles.

Temperature also influences performance by altering electrical conductivity, air density, and particle behavior during fragmentation (Yi et al., 2022). In industrial systems, these variables fluctuate continuously with feed composition and throughput, leading to non-steady-state conditions and variable separation efficiency.

Although recent studies on adaptive control systems show potential to mitigate these effects, industrial implementation remains limited (Kia & Leiding, 2025a; Kia & Leiding, 2025b).

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Table 7 summarizes the main technical limitations of ECS and the mechanisms responsible for performance losses across different applications.

Table 7. Major technical limitations of eddy current separation and their impact on performance. Adapted from Bin et al. (2022), Shan et al. (2024), Bai et al. (2023), and Yi et al. (2022).

Limitation	Mechanism	Impact on Performance
Fine particles (<5 mm)	Low induced current	Sharp efficiency loss
Mixed feed	Particle interaction	Reduced selectivity
Composite materials	Discontinuous conductivity	Poor separation
Moisture	Agglomeration and cohesion	Lower recovery
Temperature variation	Conductivity changes	Instability

Table 7 indicates that most limitations originate from reduced induced currents or complex particle interactions. Fine particles and composite materials are the most critical challenges, leading to significant efficiency losses and reduced process stability.

ECS performance is governed by particle size, composite structure, and feed variability. These factors interact non-linearly, defining a narrow operating window for efficient separation. Figure 6 summarizes their combined effects on recovery, selectivity, and process stability.

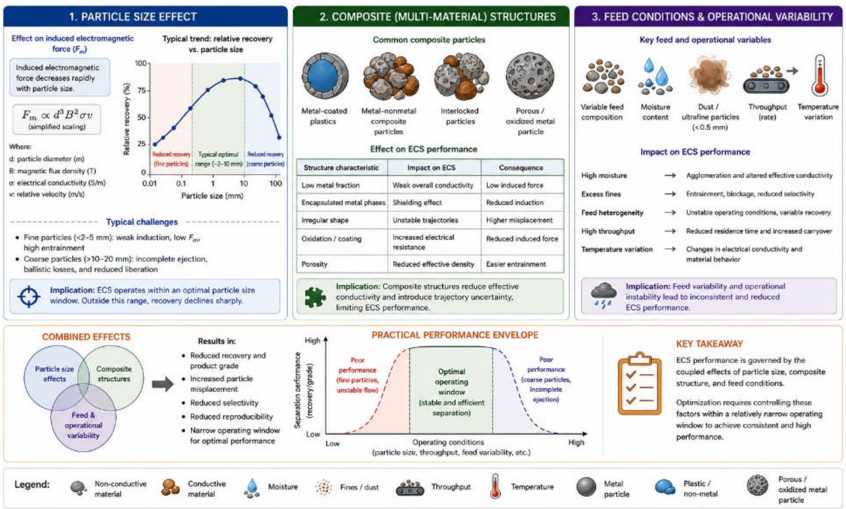

Figure 6.Key limitations affecting ECS performance: particle size, composite structure, and feed conditions. Adapted from Bin et al. (2022), Shan et al. (2024), and Kia & Leiding (2025a).

Figure 6 summarizes the main physical and operational constraints of ECS. The combined effect of fine particle size, composite structures, and feed variability defines the practical performance envelope of the technology.

Critical assessment

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

The limitations discussed are not incremental—they are structural. ECS performance is constrained by electromagnetic induction physics and cannot be fully overcome through incremental design improvements alone.

Three limitations stand out: reduced efficiency for fine particles (<2–5 mm), poor performance with composite and multi-material particles, and sensitivity to feed variability and moisture. These factors explain why ECS is increasingly used in hybrid systems rather than on its own.

Another gap is the lack of industrial-scale validation under real operating conditions. Many studies show optimized results based on controlled feeds, not accounting for the variability in real recycling streams.

Addressing these challenges requires a shift from isolated optimization toward system-level integration, combining ECS with complementary separation technologies and advanced monitoring and control strategies.

Section 8 examines how ECS is integrated within hybrid flowsheets to overcome these limitations and improve overall process performance.

8. Integration with Other Separation Technologies

Eddy current separation is rarely used on its own in modern recycling. Its limitations with fine particles, composites, and mixed feeds mean it needs to be combined with other technologies. Industrial flowsheets are hybrid, blending ECS with mechanical, physical, and sensor-based methods to enhance recovery and grade.

8.1. Magnetic, density, and physical separation routes

In most industrial setups, ECS is placed between magnetic and density separation. Magnetic separators first remove ferrous metals, reducing interference and boosting ECS selectivity; this pre-treatment can improve ECS efficiency by 10–20%, especially in mixed scrap streams (Boelens et al., 2025).

After ECS, density-based methods such as air tables or heavy-media separation refine non-ferrous fractions by exploiting density differences that ECS cannot resolve, especially for metals with similar electrical conductivity.

A typical hybrid sequence is:

• Magnetic separation → ECS → density separation

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

This configuration is widely applied in MSWI bottom ash and slag processing, where mineral contamination is significant. Multi-stage physical separation can increase overall metal recovery by 15–30% compared to ECS alone (Adhiwiguna et al., 2025).

However, density-based systems introduce additional challenges, including water consumption in wet processes, sensitivity to particle shape and size distribution, and increased operational complexity (Pfandl et al., 2020).

8.2. XRF, XRT, and sensor-based sorting

Sensor-based sorting technologies, like XRF and XRT, complement ECS by identifying materials through elemental composition and density contrast, aiding in alloy separation, contaminant removal, and upgrading metal streams to smelter-grade purity.

Industrial systems combining ECS with XRT can reach over 95–98% purity for aluminum and improve recovery of metals like copper and zinc (Flamme et al., 2024; Kölking et al., 2024). Usually, sensor-based sorting follows ECS as a refining step, as pre-concentration of conductive materials reduces sensor load and improves detection.

Despite their effectiveness, these systems have high capital costs, need stable feed conditions, and lower throughput (2–10 t/h) than ECS, limiting their use in high-capacity lines.

8.3. Vision-based and machine-vision sorting

Machine vision systems are a cheaper alternative to X-ray methods, using features like shape, color, and texture for classification. Recent advances combine machine vision with ECS for adaptive sorting, adjusting operating conditions in real time based on feed characteristics.

Reported improvements in separation efficiency range from 5–15% when machine vision is used to support ECS operation and particle classification (Irsyad & Dhelika, 2024; Li et al., 2024). These gains are primarily associated with better control of feed uniformity and reduced misclassification at the ECS stage.

However, vision-based systems have limitations: performance depends on lighting, they struggle with similar materials, and can't detect internal composition (Huang et al., 2022). Machine vision is best combined with ECS and other sensors, not used alone.

8.4. Hybrid flowsheets for WEEE and battery waste

Hybrid flowsheets are standard in WEEE and battery recycling, combining multiple separation stages for complex feeds. WEEE routes include shredding, magnetic separation, ECS, sensor-based sorting, and refining. Battery recycling adds pre-treatment, classification,

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

and hydrometallurgical processing due to fine particles and composites (Bi et al., 2021; de Buzin et al., 2021).

These integrated systems can achieve overall recoveries above 85–95% for major metals and reduce downstream processing costs. However, the increased complexity also leads to higher CAPEX, greater operational sensitivity, and increased maintenance requirements (Gulliani et al., 2023).

Table 8 summarizes how ECS is integrated with complementary technologies in hybrid flowsheets to overcome its intrinsic limitations and improve overall process efficiency.

Table 8. Integration of eddy current separation with complementary technologies in hybrid processing flowsheets. Adapted from Boelens et al. (2025), Flamme et al. (2024), Kölking et al. (2024), and Williams et al. (2023).

Technology	Role in flowsheet	Strength	Limitation
Magnetic separation	Pre-treatment	Removes ferrous metals	Limited to magnetic materials
Density separation	Post-ECS refining	Separates similar conductors	Sensitive to shape
XRF/XRT sorting	Final upgrading	High purity (>95%)	High CAPEX
Machine vision	Process control	Adaptive optimization	Limited selectivity
Air classification	Fine separation	Handles fine particles	Limited precision

Table 8 shows that ECS rarely operates as a standalone process in advanced recycling systems. Its effectiveness is enhanced when combined with magnetic, density, and sensor-based technologies. Hybrid configurations improve selectivity and purity but increase system complexity and cost.

Hybrid flowsheets overcome ECS limitations, especially for fine particles and complex feeds. ECS acts as an intermediate step with magnetic, density, and sensor separations to enhance recovery and purity. Figure 7 shows integrated setups for WEEE, batteries, and residues, emphasizing ECS in multi-stage systems.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

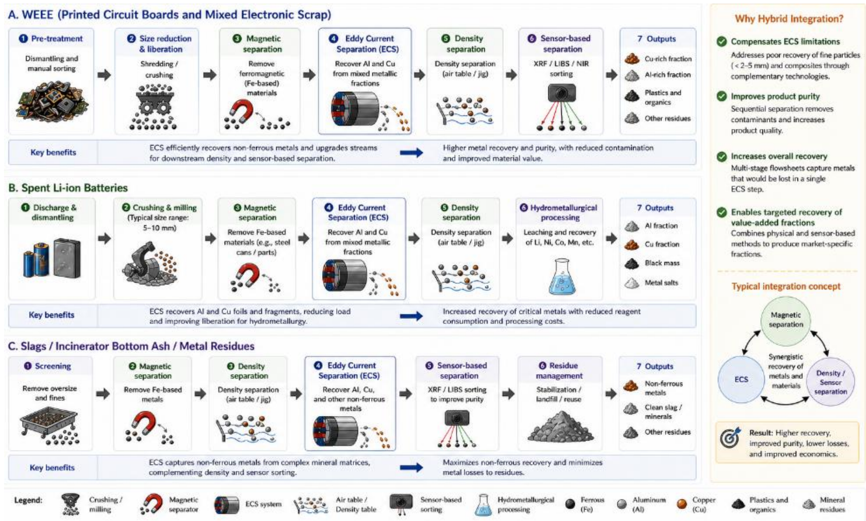

Figure 7. Hybrid flowsheets integrating ECS with magnetic, density, and sensor-based separation technologies for WEEE and battery recycling. Adapted from Bi et al. (2021), Boelens et al. (2025), and Flamme et al. (2024).

Figure 7 illustrates typical industrial flowsheets in which ECS serves as an intermediate stage. Integration with complementary technologies enables higher recovery and purity, compensating for ECS limitations in fine and composite materials.

Critical assessment

Integration is no longer optional—it is required. ECS alone cannot meet the purity and recovery targets demanded by modern recycling systems, particularly for complex and heterogeneous feeds.

Hybrid flowsheets can boost performance but entail trade-offs: higher costs, greater complexity, and greater sensitivity to feed variability. Sensor technologies offer precision but limited throughput, while mechanical methods handle large volumes but lack selectivity. ECS balances throughput and efficiency.

The main challenge is therefore not the optimization of individual units, but the integration and control of the entire process at the system level. Most studies still assess technologies in isolation, without evaluating their combined performance within full recycling flowsheets.

Future developments should focus on integrated modeling of hybrid systems, implementation of real-time monitoring and control strategies, and optimization across multiple separation stages. These approaches are essential to improve robustness, adaptability, and overall system efficiency.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Section 9 evaluates the energy consumption and environmental impact of ECS and hybrid separation systems, with particular emphasis on their role within circular economy strategies.

9. Energy Consumption and Environmental Impact

Eddy current separation is a low-energy physical technology, but its environmental impact depends on its role within recycling flowsheets, upstream processing, and downstream refining. This section assesses energy use, trade-offs, and ECS's role in circular economy systems.

9.1. Energy and exergy of aluminum recycling

In aluminum recycling, ECS consumes a small fraction of total energy, operating at 0.5–2.5 kWh/t, which is negligible compared to shredding (10–50 kWh/t) and melting/refining (500–1,500 kWh/t) (Hannula et al., 2020; Pereira, 2025a).

ECS is inherently efficient from an exergy perspective, operating near ambient temperature without phase changes, unlike pyrometallurgical processes that lose exergy through heat dissipation and irreversibility.

ECS's main contribution is indirect: it improves metal recovery and reduces contamination, lowering the energy needs of melting processes. In aluminum recycling, ECS pre-sorting cuts furnace energy use by 5–15%, depending on feed and separation (Pereira & Santos, 2025).

However, this benefit is highly dependent on the quality of the ECS concentrate. If separation efficiency is low and contamination levels remain high, the resulting energy savings in downstream processing may be limited or negligible (Yongzhen, 2024).

9.2. LCA and environmental trade-offs

Life cycle assessment (LCA) studies show that physical separation technologies like ECS have lower environmental impacts than chemical or thermal processes. They offer low emissions, minimal reagent use, and less secondary waste, making them appealing in circular economy models (Padamata et al., 2021; Mishra et al., 2024).

LCA results reveal trade-offs, as ECS depends on upstream reduction and classification, which significantly increase environmental impact. Comminution can consume 30–60% of energy, often surpassing the separation stage, shifting the burden to pre-treatment.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

System integration emerges as a critical factor in determining overall performance. Inefficient flowsheet design can lead to reprocessing of intermediate streams, increased material losses, and higher cumulative energy demand. These inefficiencies can offset the intrinsic environmental advantages of ECS if not properly managed (Toro et al., 2023).

LCA studies show that transport and logistics heavily influence decentralized recycling, which has fragmented flows. While ECS doesn't directly address this, better separation efficiency reduces the material requiring downstream processing and transport, indirectly lowering environmental impact.

9.3. Circular economy and industrial sustainability

Eddy Current Separation (ECS) is vital in circular economies by recovering secondary raw materials from complex waste streams. It boosts metal recovery, cuts landfill waste, and enhances resource efficiency. These gains are crucial in high-volume recycling, where small improvements lead to notable material and energy savings.

In aluminum recycling, secondary production uses up to 95% less energy than primary. ECS aids this by enabling efficient sorting and pre-concentration of aluminum prior to remelting, thereby improving feed quality and process efficiency (Langan et al., 2024; Pereira, 2026f). ECS also supports the recovery of residual metallic phases in slags and residues that would otherwise be lost, enhancing resource use and reducing the environmental impact of waste disposal (Pereira, 2025c; Pereira, 2025a).

However, ECS alone does not guarantee circularity. Its effectiveness depends strongly on integration with downstream processes that can recover, upgrade, and refine the separated metals. Without such integration, recovered fractions may remain contaminated, downgraded, or ultimately discarded, limiting their contribution to closed-loop material cycles.

9.4. Metal recovery from secondary residues

Secondary residues like WEEE, bottom ash, and battery waste are key sources of valuable metals. ECS is often used as a pre-treatment to concentrate conductive fractions, improve processing, and remove metallic components before hydrometallurgical or thermal treatment. This reduces contaminants and boosts process selectivity.

Pre-concentration with ECS reduces reagent use in later leaching stages by 10–25%, depending on feed and system setup (Rao et al., 2020; Paranjape & Yadav, 2023). ECS often

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

separates base metals from electronic waste prior to precious metal recovery, thereby enhancing efficiency and environmental performance (Saha et al., 2024).

Despite these benefits, ECS does not directly recover critical elements such as lithium or rare earths. Its role remains indirect, focused on upgrading feed streams and enabling more efficient downstream extraction. This distinction is important when evaluating its contribution within integrated recycling systems.

Table 9 summarizes typical energy consumption values for ECS and its position in the overall recycling chain, highlighting the relatively low contribution of mechanical separation compared to upstream comminution and downstream metallurgical processing.

Table 9. Energy consumption and environmental impact associated with ECS and related recycling processes. Adapted from Hannula et al. (2020), Pereira (2025a), Pereira and Santos (2025), and Toro et al. (2023).

Parameter	Typical Value	Impact
ECS energy consumption	0.5–2.5 kWh/t	Low direct energy use
Shredding energy	10–50 kWh/t	Major upstream contributor
Aluminum melting energy	500–1,500 kWh/t	Dominant energy demand
Energy savings via ECS	5–15%	Indirect benefit
LCA impact	Low	Depends on system integration

Table 9 shows that ECS has a relatively low direct energy demand compared to shredding and especially aluminum melting, which dominates the total energy balance. The main contribution of ECS lies in indirect energy savings, improving feed quality and reducing downstream processing requirements.

Despite extensive ECS research, key limitations remain under realistic conditions. Studies focus on isolated aspects like particle behavior, equipment, or modeling, without assessing their overall impact. Critical gaps exist in fine particle recovery, composite behavior, scale-up, and system integration. Identifying and prioritizing these gaps is essential for guiding future research and industrial use. Figure 8 summarizes the main gaps and their effects on ECS performance and deployment.

JIRRS
Journal International Review of Research Studies

Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

#	RESEARCH GAP	Why it matters	Impact on ECS performance and deployment	Current status in the literature	Priority for research	Key actions to address the gap
1	Lack of integration of ECS within full recovery chains for strategic metals (Li, Ga, REEs, etc.)	ECS is often studied in isolation, without evaluating its impact on downstream recovery, product purity, and economics.	High – Uncertain overall benefit at system level; High – Limits system-level optimization; High – May hinder industrial adoption	Very limited (<10% of published studies) Mostly bench-scale studies of unit operations	P1 Critical	Develop and validate integrated flowsheets from pre-treatment to final metal recovery. Perform pilot-scale, mass-balanced studies including downstream integration. Assess techno-economic and environmental performance (TEA/LCA).
2	Limited understanding of effects of composite and multi-material particles	Composite particles are common in real feeds and reduce ECS efficiency, but mechanisms are not well quantified.	High – Reduced recovery and selectivity; Medium – Increased performance variability; Medium – Design and scale-up uncertainty	Limited (10–25% of studies) Mostly preliminary or basic investigations	P2 High	Systematically characterize composite particles (structure, liberation, conductivity). Quantify shielding, coating, and locking mechanisms. Develop and validate predictive models for composite particle behavior.
3	Scarcity of data for fine particles (< 2–5 mm)	Fine particles are difficult to separate and are often lost, reducing overall recovery and value.	High – Low recovery of fine particles; High – Increased metal losses; Medium – Limits applicability to complex feeds	Limited (10–20% of studies) Predominantly lab-scale studies	P2 High	Systematic studies for fine particle behavior and limits. Optimize air flow, rotor design, and particle residence time for fines. Investigate hybrid pre-concentration and separation strategies.
4	Lack of standardization in reporting and performance metrics	Heterogeneous methods and metrics prevent reliable comparison and slow technology development.	Medium – Difficult comparison; Medium – Low data reliability; Medium – Reproducibility issues	Moderate (25–50% of studies) Inconsistent performance metrics and operating conditions	P3 Medium	Establish standardized reporting frameworks (recovery, grade, selectivity, energy, etc.). Define standardized test protocols and reference materials. Develop open-access databases for ECS studies.
5	Limited real-time monitoring and process control	Most ECS systems operate open-loop, leading to suboptimal and variable performance.	Medium – Performance variability; Medium – Higher losses; Medium – Operational instability	Limited (10–25% of studies) Emerging but not yet widely validated solutions	P3 Medium	Develop and integrate real-time sensors (NIR, XRF, cameras, coil monitoring). Implement closed-loop monitoring and control systems. Use data analytics and machine learning for real-time optimization.
6	Insufficient evaluation of energy consumption and environmental impacts	Energy use and environmental impacts are arrely quantified in ECS studies.	Medium – Uncertain sustainability; Medium – Poor life-cycle data; Low – Limits green validation	Very limited (<10% of published studies) Largely absent in the literature	P4 Low–Medium	Measure and report energy use and emissions. Conduct life-cycle assessment (LCA). Benchmark against alternative separation technologies.
7	High capital and operational costs; limited economic studies	Economic assessments for industrial scale are rare and uncertain.	Medium – Unclear ROI; Medium – Limits investment; Medium – Scale-up risk	Very limited (<10% of published studies) Predominantly qualitative assessments	P4 Low–Medium	Develop capex/opex models for industrial scale. Validate cost models in pilot and demonstration plants. Assess economic sensitivity and scenarios.

Impact scale: High, Medium, Low
Current status scale (based on % of published studies addressing the gap): Very limited (<10%), Limited (10–25%), Moderate (25–50%), High (>50%)
Priority scale: P1 Critical, P2 High, P3 Medium, P4 Low–Medium

Figure 8. Energy distribution and environmental impact of ECS within integrated recycling systems. Adapted from Hannula et al. (2020), Toro et al. (2023), and Pereira (2025a).

Figure 8 shows that ECS contributes minimally to total energy consumption. The main environmental benefits arise from improved separation efficiency, which reduces downstream processing requirements.

Critical assessment

ECS is often called a "green" technology, but this needs qualification. Its direct energy use is low, but the environmental impact depends on the entire process chain. The separation stage contributes little to total energy but significantly influences downstream efficiency by enhancing feed quality and reducing processing.

The environmental benefits of ECS are largely indirect and depend on process integration. Poorly designed flowsheets can negate these benefits through reprocessing, material losses, or higher energy use. Additionally, life cycle assessments are limited and often rely on lab data, which reduces their relevance to industrial systems.

A limitation is the lack of exergy-based analyses, as conventional energy metrics do not fully capture thermodynamic inefficiencies or irreversibilities in separation processes. This leaves the true performance of ECS in integrated systems not fully understood.

Claims about circular economy benefits should be approached with caution. ECS aids material recovery but does not ensure effective reuse. Moving recovered materials into production depends on factors like quality, demand, and processing capabilities.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Against this background, Section 10 explores emerging trends aimed at addressing these limitations, including high-frequency ECS systems, artificial intelligence integration, and new applications targeting critical metal recovery

10. Emerging Trends

Eddy current separation is evolving from a mature mechanical system to a high-precision, digitally assisted one. This shift responds to more complex waste streams, stricter purity standards, and the need for critical metals. Developments aim to expand ECS use beyond its traditional limits, particularly forfine particles, mixed metals, and data-driven operations.

10.1. High-frequency and advanced ECS designs

One of the most active areas of development in ECS is the use of high-frequency magnetic systems. Increasing rotor frequency beyond conventional ranges enhances eddy current induction, particularly for smaller particles that are otherwise difficult to separate. Recent experimental and numerical studies indicate that higher frequencies can improve separation efficiency for particles in the 2–5 mm range by approximately 10–30%, although gains become marginal below 2 mm due to intrinsic electromagnetic limitations (Shan et al., 2025d; Abedini-Gourtani & Tabesh, 2025).

Advanced rotor designs use optimized Halbach arrays, smaller air gaps, and lightweight sleeves to boost magnetic fields and energy transfer, creating stronger forces on particles. However, these improvements also pose mechanical challenges, especially regarding rotor stability, thermal effects, and wear at high speeds (Park & Ahn, 2025).

Despite these advances, high-frequency ECS does not fully overcome the limitations associated with fine particles. Although performance improvements are measurable, they remain incremental because reducing particle size inherently limits induced current generation. Consequently, high-frequency systems should be viewed as an optimization strategy rather than a complete solution to the fine particle separation challenge.

10.2. Vertical ECS and difficult metal–metal separation

Traditional ECS systems mainly separate conductive metals from non-metals. However, distinguishing metals like aluminum and copper is challenging because they respond similarly to eddy currents.

Vertical ECS configurations offer a promising solution by varying the magnetic field orientation to alter particle paths and improve the separation of materials with similar

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

conductivities. Studies show enhanced separation of aluminum and copper, with efficiency gains of 10–25% in controlled settings (Shan et al., 2025a; 2025b).

Despite these advantages, industrial adoption remains limited. Vertical ECS systems typically exhibit lower throughput compared to conventional horizontal configurations and are more sensitive to variations in feed composition. In addition, their mechanical design is more complex, which increases capital and operational costs. As a result, their application is currently restricted mainly to pilot-scale studies and specialized separation tasks.

10.3. Digital twin, IoT, and intelligent monitoring

Digitalization is progressively transforming ECS operation by enabling continuous monitoring and data-driven control of key process variables. The integration of digital twins and IoT-based sensing systems allows real-time tracking of rotor speed, belt velocity, feed composition, and separation efficiency, creating a dynamic representation of the process under actual operating conditions (Kia & Leiding, 2025a; Kia et al., 2025).

Digital twins go beyond monitoring, enabling simulation-based optimization. They let operators evaluate parameter adjustments in real time, improving process stability and reducing variability from fluctuating feed characteristics. Early implementations suggest these systems can boost recovery by about 5–15% and support predictive maintenance by detecting system deviations.

Despite advantages, industrial deployment remains limited due to data shortages, integration challenges with legacy systems, and high costs. These restrict adoption to pilots or advanced facilities, though ongoing advances may boost broader use (Kia & Leiding, 2025b).

10.4. AI, deep learning, and smart scrap classification

Artificial intelligence enhances ECS through data-driven optimization and adaptive control. It classifies scrap, optimizes parameters, and sorts with sensors. Deep learning uses large datasets from vision and sensors to improve material identification in complex feeds (Chen et al., 2021; Williams et al., 2023).

Reported results indicate 5–20% improvement in separation efficiency and better handling of mixed feeds. These systems enable real-time control of parameters such as rotor speed and feed distribution, resulting in more stable, efficient operations. The advantages are especially clear when AI enhances hybrid systems that combine ECS with sensor-based sorting.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Despite advances, AI effectiveness relies on data quality and availability. Models lack robustness to changes in feed, particle size, and conditions, making generalization difficult. Large-scale use is still developing (Huang et al., 2022; Langan et al., 2024).

10.5. Critical metals in future recycling systems

The growing demand for critical metals—such as lithium, gallium, and rare earth elements—has shifted the focus of recycling technologies toward higher selectivity and system efficiency. In this context, ECS is not selective for these elements, but it plays a strategic role in pre-concentration and stream preparation, particularly in complex and heterogeneous waste streams.

Future recycling systems will rely on ECS to remove contaminants, concentrate metals, and improve recovery. For example, in battery recycling, ECS separates aluminum and copper foils prior to hydrometallurgy, thereby improving selectivity and reducing reagent consumption (Li et al., 2024). These pre-treatments stabilize feed and boost extraction efficiency.

Emerging applications indicate ECS could process ultrafine metallic fractions, complex composites, and support decentralized recycling (Pereira, 2026d; Pereira, 2025b; Kulenova et al., 2026). These are under investigation and need validation for industrial-scale throughput, robustness, and cost-effectiveness.

Despite advances, ECS's role remains indirect. It is unlikely to replace chemical or thermal extraction but serves as an enabling technology in integrated flowsheets. Its value lies in enhancing feed quality, reducing variability, and boosting overall resource recovery efficiency.

Table 10 summarizes the main emerging trends in eddy current separation and their expected impact on process performance, reflecting current research efforts to address persistent technical limitations and expand the applicability of ECS in next-generation recycling systems.

Table 10. Emerging trends in eddy current separation, expected benefits, and associated limitations. Adapted from Shan et al. (2025d), Kia & Leiding (2025a, 2025b), and Langan et al. (2024).

Trend	Expected Benefit	Limitation
High-frequency ECS	Improved fine particle separation	Mechanical constraints
Vertical ECS	Better metal–metal separation	Low throughput
Digital twin / IoT	Process optimization	Data availability
AI and deep learning	Adaptive control	Limited generalization
Critical metal recovery	Improved pre-treatment	Indirect role

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

Table 10 shows that most emerging solutions focus on fine-particle separation, process optimization, and system integration. Although these approaches offer clear performance improvements, they remain constrained by technical complexity, data requirements, and scale-up challenges.

Recent advances in Eddy Current Separation (ECS) aim to overcome limitations such as poor recovery of fine particles and low selectivity in complex feeds. New approaches include high-frequency excitation, vertical separator designs, and AI for real-time control. While promising, their industrial use is limited by validation challenges. Figure 9 summarizes these trends and their potential impact.

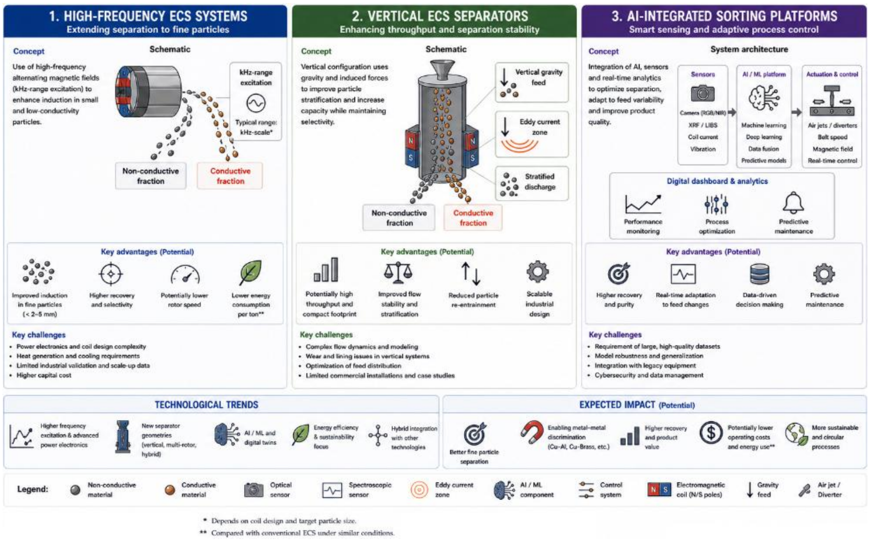

Figure 9. Emerging ECS technologies: high-frequency systems, vertical separators, and AI-integrated sorting platforms. Adapted from Shan et al. (2025d), Kia et al. (2025), and Williams et al. (2023).

Figure 9 summarizes the technological evolution of ECS. Advances focus on improving fine particle separation, enabling metal–metal discrimination, and integrating digital control systems.

Critical assessment

Emerging trends in ECS are largely evolutionary rather than disruptive. Current developments focus on extending the technology's operational envelope rather than redefining its fundamental principles. Three main directions can be identified: incremental improvements in electromagnetic design, integration with digital and AI-based systems, and expansion toward increasingly complex recycling streams.

Advances in rotor configuration, magnetic field intensity, and frequency control have improved separation performance, particularly in the intermediate particle size range. At the

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

same time, the incorporation of digital tools—such as real-time monitoring, digital twins, and machine learning—has introduced new possibilities for process optimization and adaptive control. These developments are especially relevant in heterogeneous waste streams, where feed variability is a dominant factor.

Despite advances, key limitations persist: low separation efficiency for fine particles due to weak induced currents; sensitivity to feed composition that affects stability; and ECS's lack of selectivity for critical metals, limiting it to pre-treatment rather than recovery.

A significant gap persists between laboratory-scale innovation and industrial implementation. Technologies such as vertical ECS configurations and AI-integrated systems show promising results under controlled conditions, but their application at industrial scale remains limited. Challenges include throughput constraints, system complexity, and integration with existing infrastructure.

Future progress in ECS will depend less on isolated technological improvements and more on system-level integration. The combination of ECS with complementary separation technologies, digital monitoring, and optimized flowsheets will be critical to achieving meaningful performance gains.

Section 11 presents a critical synthesis of the reviewed literature, highlighting the main research gaps and proposing directions for future development of ECS systems.

11. Critical Synthesis and Research Gaps

This section summarizes the main findings and highlights structural limitations in eddy current separation (ECS). Although industrially established, the literature shows an imbalance between understanding, laboratory testing, and industrial validation. These systemic gaps impact ECS design, scale-up, and optimization.

11.1. Lack of standardized ECS testing protocols

A major limitation is the lack of standardized testing methods, leading to significant variations in reported results due to differences in particle size, feed, rotor setup, and operational parameters. Metrics like recovery and separation efficiency are often inconsistently defined—some use simplified mass balances, while others use trajectory- or force-based methods (Bin et al., 2022; Shan et al., 2024).

Unlike fields that have adopted structured frameworks such as PRISMA 2020 for methodological consistency (Page et al., 2021), ECS research lacks a unified experimental

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

approach. This limits reproducibility and prevents meaningful comparison between studies conducted under different conditions.

As a result, reported efficiency improvements in the range of 10–30% are frequently not directly comparable. This reduces their practical relevance and complicates the translation of laboratory findings into industrial applications.

11.2. Limited industrial-scale validation

Most ECS studies remain confined to laboratory or pilot scales, with limited validation under industrial conditions. Available large-scale studies are sparse and often lack the level of detail required for rigorous assessment. Critical operational parameters are frequently omitted, including throughput under real conditions (t/h), long-term stability, wear and maintenance behavior, and energy consumption at scale.

This lack of reporting isn't trivial. Industrial ECS systems operate under variable feed conditions, with fluctuations in particle size, composition, and moisture content, which directly affect performance. Labs report over 90% recovery for coarse particles (>10 mm), but in industry, efficiencies are lower due to feed heterogeneity, mechanical limits, and process disturbances (Huang et al., 2024; Boelens et al., 2025).

The result is a disconnect between academic research and industrial practice. Models from experiments are often extrapolated without validation, leading to overly optimistic predictions that are not reproducible at scale. This gap reduces confidence in scale-up methods and shows the need for standardized reports on industrial ECS performance, including operation, maintenance, and energy data.

11.3. Fine-particle ECS remains unresolved

The separation of fine particles (<2–3 mm) remains ECS's main technical limitation. Efficiency drops sharply below 5 mm, with unstable, near-random trajectories below 2 mm. Interparticle interactions, such as collisions, further reduce selectivity (Bin et al., 2022; Huang et al., 2021; Shan et al., 2025a).

Even with high-frequency rotors and optimized magnets, performance improvements are incremental. The main limitation is the reduced conductive volume of fine particles, which limits eddy currents. This causes electromagnetic force to be insufficient to overcome gravity, drag, and turbulence, with aerodynamic effects increasingly controlling particle motion and reducing trajectory differentiation.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

This limitation has significant industrial implications. Fine fractions often represent 20–50% of the total material in streams such as WEEE and bottom ash. In many cases, these fractions contain a substantial portion of valuable metals yet are recovered inefficiently by ECS. Consequently, fine particles are either lost or require additional processing routes, increasing both operational complexity and overall system cost.

11.4. Need for robust multiphysics models

Current ECS modeling is fragmented, focusing on isolated phenomena such as electromagnetic induction, particle trajectories, or fluid drag, without capturing the coupled interactions that influence actual separation behavior.

A consistent ECS description requires integrating multiple domains: electromagnetic fields via Maxwell's equations, particle motion through Newtonian mechanics, and gas–particle interactions through fluid dynamics, including drag and turbulence. Coupling between these domains is essential because induced currents depend on particle position and velocity, while electromagnetic forces and aerodynamics influence particle trajectories.

Fully coupled multiphysics models are rare, as existing ones are computationally demanding and limited to simple geometries or small particles (Ye et al., 2020; Merahi et al., 2020; Bin et al., 2024; Ouili et al., 2023). Most are descriptive rather than predictive, reproducing trends in controlled settings but lacking robustness in complex industrial systems.

This limitation hinders scale-up and process optimization. Without validated models, design depends on empirical adjustments and testing. Developing reduced-order multiphysics models and validated simulations is crucial for reliable industrial ECS deployment.

11.5. Techno-economic and LCA gaps

Despite ECS's industrial importance, TEA and LCA remain underrepresented, with studies primarily focusing on aluminum recycling energy use and metal recovery benefits (Hannula et al., 2020; Loibl & Espinoza, 2021; Zhu et al., 2025).

Key economic parameters like CAPEX, OPEX, and efficiency benefits are rarely quantified. ECS typically uses 0.5-2.5 kWh/t, but its economics depend on recovery efficiency and downstream performance.

Without integrated TEA and LCA approaches, it remains difficult to assess the real value of technological improvements. This gap limits the ability to compare ECS with alternative technologies and to support decision-making at an industrial scale.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

11.6. Strategic metals and circular-economy agenda

The transition toward a circular economy has intensified interest in recovering critical metals such as lithium, gallium, and rare earth elements. In this context, ECS plays an indirect but important role by concentrating conductive fractions, removing contaminants, and improving the efficiency of downstream processing steps (Pereira, 2026e; Pereira, 2026d; Pereira, 2026c; Pereira, 2025l).

However, ECS is not selective for these elements, and its function is largely limited to pre-treatment. This distinction is often overlooked in the literature, where the contribution of ECS to critical metal recovery is sometimes overstated. In practice, its value lies in upgrading feed streams rather than directly enabling selective extraction.

A major gap remains in the lack of studies that integrate ECS into complete recovery chains for strategic metals. Most research treats ECS as an isolated unit operation, without considering its interaction with subsequent hydrometallurgical or pyrometallurgical processes. This limits the understanding of its true impact at the system level.

Table 11 consolidates the main research gaps identified in this review and evaluates their impact on ECS performance and industrial deployment, highlighting priorities for future development and scale-up.

Table 11. Key research gaps in eddy current separation and their impact on technology development. Adapted from Bin et al. (2022), Shan et al. (2024), Hannula et al. (2020), Pereira et al. (2025) and Pereira (2025d).

Research gap	Impact on technology	Priority level
Lack of standardized testing	Poor reproducibility	High
Limited industrial validation	Uncertain scale-up	High
Fine-particle inefficiency	Loss of valuable metals	Critical
Weak multiphysics modeling	Limited predictability	High
Missing TEA/LCA studies	Poor economic assessment	High
Limited focus on critical metals	Incomplete circular integration	Medium

Table 11 indicates that the most critical challenges are related to fine-particle separation, lack of standardized methodologies, and limited industrial validation. These gaps directly affect process reliability, scalability, and economic feasibility, reinforcing the need for integrated research approaches.

Despite advances in Eddy Current Separation (ECS), knowledge remains fragmented across physics, design, and integration. Most studies focus on isolated aspects like trajectory modeling or sensor development, with limited attention to their combined effects under real, heterogeneous feed conditions. Challenges in fine particle recovery, multi-material

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

discrimination, and scaling up persist. Understanding these gaps is vital for future progress. Figure 10 links constraints to new research and system pathways.

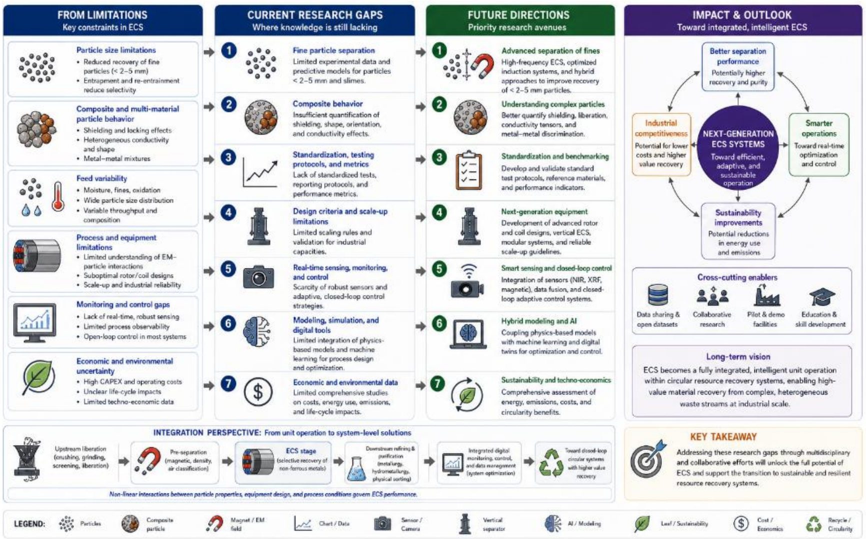

Figure 10. Research gaps and future directions in ECS: from fundamental limitations to system-level integration. Adapted from Bin et al. (2022), Shan et al. (2025d), and Pereira (2025b).

Figure 10 shows the hierarchy of ECS challenges, from particle–field interactions to system integration in circular economies. Although progress has been made in modeling, design, and sensing, these efforts remain fragmented and are rarely tested in real-world industries. Bridging the gap needs moving from component focus to system-level strategies.

Future research should move beyond incremental improvements to address systemic limitations. Key directions include developing standardized testing protocols to ensure comparability and reproducibility, expanding industrial datasets on long-term performance and feed variability, focusing on fine-particle separation via ECS and complementary methods, creating multiphysics models to predict particle and process interactions, and integrating ECS into techno-economic and circular-economy assessments to evaluate its real impact.

Additionally, the application of artificial intelligence and digital twins should be oriented toward process-level optimization and decision support, not just component improvements. This approach is essential to unlock ECS's full potential in complex, heterogeneous recycling systems.

Critical synthesis

ECS is mature but not fully optimized. It excels in coarse particle separation and pre-treatment, achieving high recoveries of non-ferrous metals in controlled conditions. However, it struggles with fine particles and complex feeds, where performance and selectivity decline.

JIRRS
Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

The field remains fragmented with experimental studies, modeling, and applications developed in isolation, limiting cross-validation. Consequently, advances often don't translate into better industrial performance, restricting research impact.

The next ECS development phase relies on integrating physics-based and data-driven methods, linking ECS with broader process chains—pre-treatment, separation, downstream refining—and positioning it within circular resource recovery systems, focusing on system efficiency, value recovery, and sustainability.

Without this transition to integrated frameworks, improvements will likely stay incremental and inadequate for advanced recycling demands. This review highlights the evolving role of ECS in next-generation resource recovery.

12. Conclusions

This review critically evaluated eddy current separation (ECS) from fundamental principles to industrial implementation. The analysis confirms that ECS is a robust, widely deployed technology for recovering non-ferrous metals, particularly aluminum and copper, from heterogeneous waste streams. Its industrial relevance is well established across WEEE processing, aluminum recycling, bottom ash treatment, and metallurgical residue valorization.

ECS performance depends on electromagnetic induction, particle conductivity, and trajectory. Key parameters—rotor frequency, belt speed, particle size, and feed—affect separation efficiency. Optimized conditions achieve over 90% recovery for coarse fractions (>10 mm), with industrial throughput of 10–100 t/h.

The review highlights key limitations: separation efficiency drops sharply for particles under 5 mm and becomes unstable below 2–3 mm. Composite and multilayer materials complicate separation due to heterogeneous conductivity. Moisture and feed variability add instability. These issues impact many modern waste streams, especially in WEEE and battery recycling.

A second major constraint is the lack of standardization. Experimental methodologies, performance metrics, and reporting practices vary widely. This prevents meaningful comparison between studies and limits the transferability of laboratory results to industrial systems. Moreover, industrial-scale validation remains insufficient, with few studies reporting long-term performance, operational variability, or economic data.

Despite these challenges, ECS remains a key enabling technology in integrated recycling systems. Its role as a pre-concentration step is critical to improving downstream

JIRRS Journal International Review of Research Studies
Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

processes, including hydrometallurgy, pyrometallurgy, and sensor-based sorting. In hybrid flowsheets, ECS improves feed quality, reduces processing costs, and enhances overall system efficiency.

Looking forward, several technological directions show strong potential. High-frequency and advanced rotor designs can increase separation forces. Vertical ECS configurations offer improved metal–metal separation. The integration of machine learning, digital twins, and sensor-based control systems enables real-time optimization and adaptive operation. These developments are particularly relevant for complex and variable waste streams.

The role of ECS in the recovery of critical and strategic metals is expected to grow. Although ECS is not selective for specific elements, it plays a crucial role in preparing and upgrading feedstocks for downstream recovery. As demand for metals such as lithium, gallium, and rare earth elements increases, ECS will remain an essential component of circular resource systems.

From a sustainability perspective, ECS offers low energy consumption—typically 0.5–2.5 kWh/t—and helps reduce landfill disposal and primary resource extraction. Its integration into circular economy frameworks is therefore both technically and environmentally justified.

In conclusion, ECS is a mature yet evolving technology. Its future impact will depend on addressing key gaps: efficient separation of fine particles, development of predictive multiphysics models, standardization of testing protocols, and integration with techno-economic and life cycle assessments. Advancing these areas will be essential to unlock the full potential of ECS in next-generation recycling systems.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

JIRRS
Journal International Review of Research Studies

Received: 01/04/2026 - **Accepted:** 08/05/2026
Vol: 01.05
DOI: 10.66104/2rdgx921
Pages: 1-55

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Journal International Review of Research Studies

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