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RECYCLING PRINTED CIRCUIT BOARDS

RESEARCH ARTICLE

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Environmental performance analysis of innovative mechanical separation for recycling of waste printed circuit boards

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ABSTRACT

The accumulation of electronic waste (e-waste) poses growing environmental challenges, amplified by the release of toxic brominated compounds in traditional recycling approaches. Printed circuit boards (PCBs), a key component of e-waste, provide an opportunity for resource recovery through advanced mechanical separations. This study evaluates the environmental performance of a developed mechanical separation process for PCBs using the Environmental Footprint 3.1, IPCC Global Warming Potential, and Cumulative Energy Demand methods. The analyzed process attempts to recover enriched outputs, including a copper concentrate and an epoxy and ceramics concentrate, aiming at delivering an efficient metals recovery, producing phenolic derivatives, and reducing bromine emissions in downstream materials recovery. Results reveal that 7–12% of the initial waste PCBs is liberated as an epoxy-rich concentrate, which, alongside the copper fraction, demonstrates potential for impact mitigation across the recycling chain. However, the process requires a cumulative energy demand of 1658.7 MJ and emits 99.9 kg CO_2-eq per ton of PCBs. Size reduction was identified as the most energy-intensive step, due to the high energy demand of millimeter-scale material reduction needed for the inertial and electrostatic separations. Sensitivity analysis highlighted the influence of regional energy profiles, with a lower dependence on fossil-based electricity significantly reducing impacts. The study also noted the disproportionate impact of recovered materials, with the copper concentrate showing a high price-weighted CO_2-eq of 0.28 kg and 4.6 MJ energy demand per kg of liberated copper concentrate. The environmental impact per unit of economic gain for the copper concentrate evolves over the process to an order of magnitude higher than that of the initial input, with transportation dominating the impact. These findings emphasize the potential of advanced mechanical separation to address e-waste concerns, while identifying areas for improvement toward a more sustainable recycling framework.

1. Introduction

The swift rise in the use of electronic and electrical equipment (EEE) has driven a significant surge in electronic waste (e-waste), presenting major environmental and health challenges. As reported by the United Nations Institute for Training and Research, "The Global E-Waste Monitor," 62 billion kg of e-waste was generated globally in 2022 [1]. As technological advancements and consumer demands accelerate the obsolescence of EEE products, managing waste from electronic and electrical equipment (WEEE) has become a pressing issue. Among the diverse components of e-waste, printed circuit boards (PCBs) stand out due to their intricate composition, which includes both valuable and hazardous materials. Advanced mechanical treatment and separation technologies are therefore critical for recycling WEEE, particularly PCBs, to ensure resource recovery while maintaining environmental protection and economic feasibility [2].

E-waste typically contains a complex mix of ferrous and non-ferrous metals, plastics, glass fibers, and other materials, often interwoven in assemblies such as PCBs [3]. Recycling PCBs is particularly challenging due to their diverse material composition, which includes precious metals such as gold, silver, and palladium; base metals such as copper, aluminum, and tin; and hazardous substances such as lead, mercury, and brominated flame retardants (BFRs) in epoxy resins – all of which require advanced mechanical processes to efficiently recover while managing the complexity and heterogeneity of e-waste [4–6]. Growing environmental and health concerns have spurred advancements in processing BFRs found in epoxy resins used in PCBs. These compounds, particularly tetrabromobisphenol A, are widely employed to enhance fire resistance by releasing bromine radicals that interrupt combustion. However, their persistence, bioaccumulation, and associated health risks – including endocrine disruption, neurodevelopmental disorders, and carcinogenicity – have prompted regulatory action, such as the European Union's Restriction of Hazardous Substances (RoHS) directive [7]. Recycling and disposal of BFR-laden PCBs remain challenging; incineration risks emitting toxic brominated dioxins and furans, while landfilling can lead to environmental contamination [8]. Innovative methods such as supercritical fluid extraction, pyrolysis, and microwave-assisted depolymerization are emerging as promising solutions to address the challenges of recycling complex materials [9]. Among these, pyrolysis – a high-temperature decomposition process conducted in the absence of oxygen – efficiently breaks down the polymer matrix of epoxy resins into reusable monomers and valuable chemicals, typically operating within a temperature range of 400 °C to 800 °C [10]. This process produces a diverse range of outputs, including oils, gases, and char, each with potential for value-added applications. The liquid fraction, rich in phenolic compounds, can be repurposed for resin synthesis or industrial uses, while the hydrogen and light hydrocarbons in the gaseous byproducts offer prospects as fuels or chemical feedstocks, emphasizing the process's versatility and resource recovery potential [11–13].

Recent innovations in PCB recycling have shifted focus toward recovering epoxy resin through pyrolysis – a process that not only sidesteps toxic emissions but also enhances material recovery by converting the epoxy into fuels or chemical gases. This method, however, hinges on the precise isolation of epoxy from metals and ceramics, the presence of which during pyrolysis can result in metal loss or increased char weight. Traditionally, waste PCBs have been processed using pyro- and hydrometallurgical techniques to extract valuable metals such as gold and copper, but this approach comes at the cost of high-calorific plastics and often releases toxic elements unless careful separation is carried out beforehand [14,15]. Abandoning traditional pyrometallurgy may promise higher metal concentrations in the smelting input, yet it introduces significant environmental and economic challenges due to the energy-intensive and complex pretreatment processes, while also failing to recover the polymer fraction, rendering it incompatible with the principles of sustainable recycling and the waste management hierarchy.

Mechanical treatment of waste PCBs involves an interconnected sequence of processes, including dismantling, size reduction, and the separation and concentration of materials, with the primary aim of liberating valuable components from the intricate matrix of PCBs and other e-waste [16,17]. By leveraging physical properties such as density, various separation techniques, including magnetic, eddy-current, and electrostatic methods, are employed to efficiently isolate metals from plastics or conductive materials from non-conductive ones [16,18–21]. Emerging advancements in mechanical separation, such as cryogenic techniques, further enhance these processes by cooling e-waste with liquid nitrogen, rendering materials brittle and thus easier to segregate [22]. The integration of diverse methods ensures a higher recovery rate of valuable resources, promoting sustainable e-waste recycling. Yet challenges remain in managing the vast variability of e-waste types, adapting to emerging materials and technologies, and justifying the high initial investment costs of mechanical separation systems, which highlights the continued need for innovation and careful evaluation of cost-effectiveness.

This study seeks to increase the recovery rates of different materials from WPCBs, such as non-ferrous metals (aluminum, copper, precious metals); ferrous metals (iron, steel, solder, etc.); organic materials (polymers); and ceramics (fiberglass, oxide ceramics). High recovery rates are achieved through the implementation of advanced recycling methods for waste PCBs, which increase the value of both metal and non-metal fractions recovered, while also reducing emissions from unproperly treated materials [22], such as those lost during processing, e.g., through the incineration of plastics in pyrometallurgy or the generation of slags from iron, aluminum, and ceramics. The majority of available solutions for advanced recycling have migrated to the recycling industry directly from its predecessor, minerals processing [22]. While there is no shortage of means for physical separation (based on density, electrical and magnetic fields, or motion), e-waste recycling can have a higher environmental impact due to the nature of the toxic materials processed [22]. The solution under the scope of this study must be environmentally safe, assuming it will not contaminate the air, soil, or water. To tackle these challenges, the system deploys a series of filtering systems to retain dust for further treatment and reduce noise. To minimize the potential environmental footprint of the separation system, the selection of plant processes avoided technologies reliant on chemicals, water, or gases that would require purification or pose risks to, for example, the ozone layer. This study addresses inefficiencies in material recovery and concerns over bromine emissions discussed earlier in current e-waste recycling practices by evaluating the impact of a novel mechanical separation process that liberates epoxy resin from waste PCBs, while focusing on market orientation and providing a state-of-the-art review. A comprehensive environmental impact assessment of the developed separation process is performed, alongside a literature-based evaluation of the environmental impact of downstream materials recovery, such as pyrolysis. The aim is to determine whether the benefits gained from subsequent valorization steps can offset the environmental costs of the additional pretreatment processes – an aspect explored primarily through a literature-based investigation.

It is worth noting that this paper extends the discussion presented in the article titled "Sustainable e-waste recycling: environmental impact assessment of novel waste PCBs separation" [23], which is part of the same experimental campaign feasibility study. This paper offers a more comprehensive analysis of the experimental procedures and provides a deeper investigation into the environmental performance of the developed separation process.

2. Materials and methods

2.1. Composition of waste printed circuit boards

The economic value of waste PCBs hinges on their composition, with higher concentrations of precious metals such as gold, silver, platinum, or palladium driving up their worth. Depending on these factors, waste PCB prices can vary dramatically, from as little as 1 €/kg to over 40 €/kg, as observed on online trading platforms [24,25]. Table 1 summarizes the composition of the waste PCBs used in this study, provided by Atlantic Copper and KAT Metal OÜ. The analysis of PCB composition typically employs either destructive techniques, such as atomic absorption spectroscopy and inductively coupled plasma atomic emission spectrometry, or non-destructive methods, such as X-ray fluorescence and X-ray diffraction [26]. For this study, low-grade PCBs were examined, with market values in Estonia (KAT Metal Estonia OÜ) of 3.20 €/kg.

2.2. Mechanical treatment and liberation

The focus in the design of the stated separation system was to create a versatile solution that could be deployed in remote locations, thus not dependent on intensive logistics or consumables (water, gases, lubricants, chemicals, etc.). The boundaries for the design were set to reduce such dependencies, resulting in a system design that relied only on electricity and air intake. The solution was based on the basic properties of the materials, such as electroconductivity, magnetism, weight, floatability in air, inertia, and form factor. The system was built in a closed-circuit layout, which enhances control over the output by classifying the output fractions into: a) overflow, material that passed the criteria for the final product; and b) underflow, material that failed to meet the criteria and was returned for treatment once more [26]. To maximize the overflow of the product, it is essential to have both liberated materials – particles of the mono-material clean from agglomerates – and selective separation methods, such as physical separation methods targeting properties attributed to specific materials (magnetism, density, floatability, etc.) [26]. The prerequisite for selective separation is accurate liberation, achieved through selective size reduction of ductile and brittle materials contained in waste PCBs [26]. This effect was achieved by introducing impact size reduction, a selective method that targets the weakest points between materials with different strength and hardness [26]. During the test campaign, the efficiency of processes was assessed by a common parameter, which was comparable throughout the competitive processes. In the case of size reduction, it was the d100 critical size of 3.00 mm (in terms of which 100% of material is below the set size). The size reduction methods were compared based on their performance in achieving the d100 size, namely: a) dust accumulation rate, g/kg; b) energy consumption to reach the d100 size, kWh/ton; and c) relative resilience (wear resilience), €/ton.

Table 1. Composition of low-grade waste PCBs reported by Atlantic Copper and KAT Metal Estonia OÜ

Metal, %		Ceramic, %		Organic, %	
Cu	19	Al_2O_3	2	Epoxy resin	41
Si	9	SiO_2	5.7	Br	4
Fe	6.6	CaO	1.4		
Al	5	MgO	0.6		
Pb	2.2				
Sn	1.7				
Zn	0.5				
Ni	0.44				
Sb	0.4				
Cr	0.1				
Ag	28E-3				
Au	5.5E-3				
Pd	0.5E-3				
Pt	0.001E-3				

2.3. Life cycle assessment: system boundary and allocation problem

Life cycle assessment (LCA) evaluates the environmental impacts of a product, process, or activity from its creation to disposal, guiding decision-making by identifying key impacts and opportunities for improvement. The analysis in this study was conducted using SimaPro 9.5 software and the Ecoinvent 3 database, which provide reliable and transparent life cycle inventory data to assess environmental impacts, supporting companies, researchers, and policymakers in making informed, sustainable decisions [27]. The Environmental Footprint 3.1 [28], Cumulative Energy Demand, and IPCC Global Warming Potential (20-year horizon) [29] methods were applied to assess these impacts. The functional unit, chosen as processing one ton of waste PCBs, was defined respecting [30]. The system boundary for the LCA study includes size reduction, screening, and separation steps, as detailed in Section 2.2, while excluding upstream processes such as collection and manual dismantling, and downstream processes such as metals recovery, pyrolysis, and disposal. This study introduces a mechanical separation technique for isolating epoxy resin from waste PCB matrices and assesses its environmental implications. Discussions related to potential improvements in the recycling process, particularly through downstream processes such as pyrolysis, are addressed in a literature-based review investigation.

3. Results and discussion

The results showed a clear advantage of impact size reduction over the methods such as compression (between elements), traction (rolling or squeezing material through), and sheer force (cutting), as the nature of impact size reduction results in internal stresses in the target material, effectively targeting the weakest bounds internally. Such selectiveness from the process allows to reduce costs and environmental impact by requiring less intense treatment than the other processes [26]. The further treatment materials were performed in batches, as different discharges were formed using magnetics, electrostatics, and densities. While electrostatics- and magnetics-based methods have certain advantages in dealing with mixtures of metals and non-metals [26], the amount of materials in the stream for electrostatics and magnetics was overwhelming for accurate processing, yet costly due to their relatively small throughput capacity. A solution to this specific problem was designed and implemented, designated as inertial separator. The solution focused on another specific difference in the materials: floatability in the airflow [26]. The study indicated that the lightweight materials (namely plastics and ceramics weaves of PCBs) tend to retain the flat form after size reduction, as their flexibility allows them, to some extent, to restore the original form they had during PCB production. Meanwhile, the metals obtained a pseudo-spherical form due to their plasticity, and therefore the surface area of metal particles was relatively smaller than that of non-metals. The results of the study indicated the terminal velocity (m/s) for different particles (metals, non-metals) at which specific particles tend to flow away, while others cannot be sustained by airflow and drop down. The obtained results from separator yielded two fractions: metals (copper) and non-metals-rich fractions. The fraction with metals averaged around 75–80% of all the metals from the stream, while the other fraction had reduced metal content comparing to the initial feedstock.

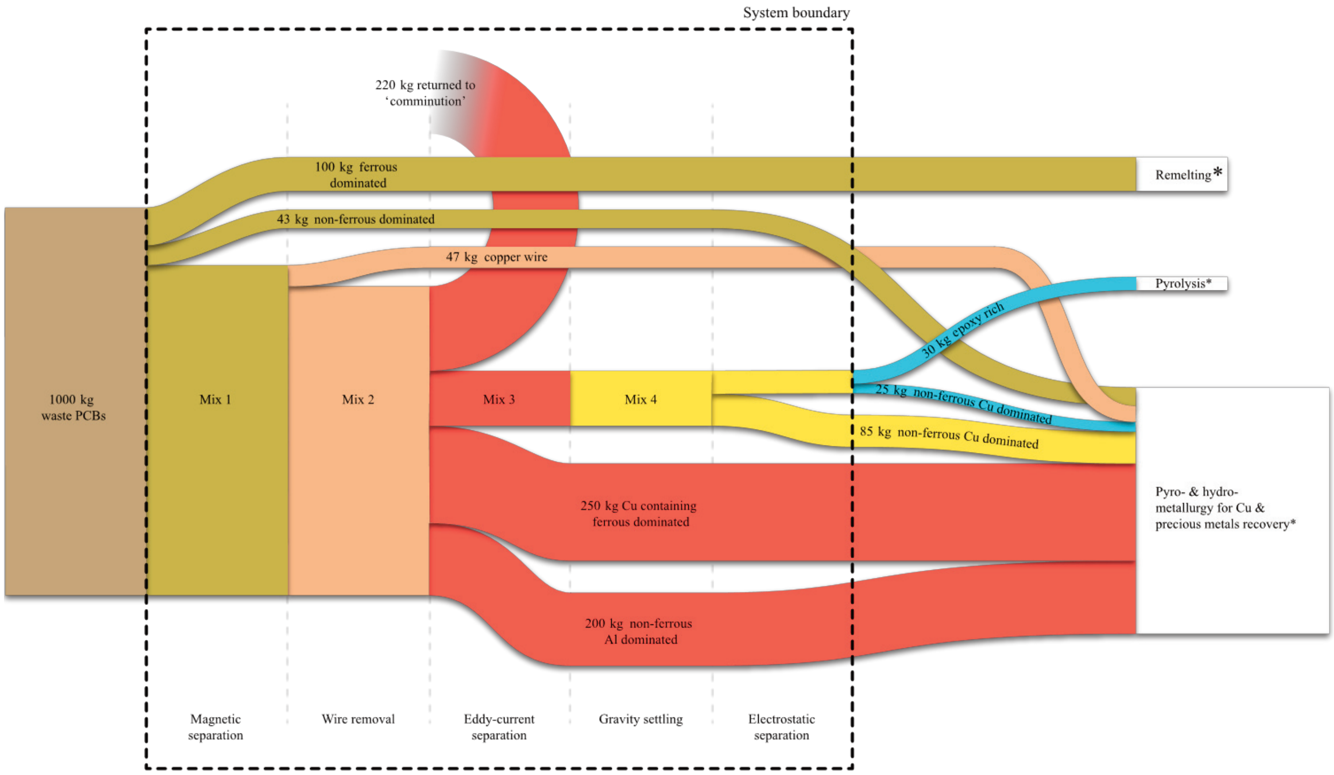
While the metals-rich fraction was discharged, the non-metals-rich fraction could be purified from metals and discharged as a byproduct. The use of the inertial separator was made possible due to well-liberated metal particles and relatively clean non-metal particles present in the feedstock. The separator, although working with fine-size powder, managed to avoid dust contamination due to the integrated filtering system. The ambient dust level near the separator rarely exceeded the normal levels during the measurements. The results from the separation plant testing confirmed the feasibility of implementing the tested technologies (size reduction and separators) in a closed-circuit pattern. The materials' stable and predictable flow allows for the upscaling of the technology to production capacities of 3 t/h and beyond. The selected size reduction method, impact, outperformed other methods (compression, traction, and sheer force). While competitive methods intensively affected the outer (harder) layer of the PCB, the impact method successfully communicated sufficient kinetic energy to the internal bounds of the PCB, effectively breaking the weakest links and liberating metals and non-metals.

The testing was carried out under conditions replicating a relevant work environment, with production capacity and minimal human interaction. As the main goal remained the recovery of precious metals (gold, silver, etc.), tracking the materials was an ongoing task and served as the main indicator for the successful separation of non-precious metals and non-metals from the main stream (pieces containing copper and precious metals). Control was asserted through methods such as XRF and graphite furnace atomic absorption spectroscopy (GF-AAS). Parameters such as the intensity of size reduction and separation were adjusted according to output analyses, focusing on concentrating all the precious metals in one fraction. The results from the pilot campaign suggested that the concentration of precious metals in the fraction could be increased by 30–40% by removing aluminum and iron. However, the findings from the separation plant testing also indicated that there is still room for improvement, as the recovery of selected materials was carried out with respect to precious metals content. The aim was to retain the previous metals in the target copper concentrate fractions that were intended to be further refined in pyro- and hydro-metallurgical processes for precious metals recovery.

Figure 1 presents the material flows throughout the separation process, with each stream tracked following [31]. The inherently heterogeneous nature of waste PCBs means that the discharges are composite, with certain elements taking prominence in specific streams [32]. Despite advancements in separation technologies, achieving separation purity beyond 80–90% remains a challenge. As a result, even at final destinations such as landfills, where recovery is economically or technically unfeasible, trace amounts of metals and polymers persist [33,34]. Approximately 7–12% of the initial waste PCBs is ultimately separated as an epoxy and ceramics concentrate, which, along with the copper concentrate, is expected to reduce the overall environmental impact across the entire recycling process chain of waste PCBs. This reduction could potentially lead to more efficient metals recovery and the production of phenol derivatives in the downstream process of pyrometallurgy and pyrolysis, respectively.

Figure 2 illustrates the evolution of CO_2-eq emissions and cumulative energy demand during the developed mechanical treatment of low-grade waste PCBs, evaluated using the IPCC Global Warming Potential method (20-year horizon) and the Cumulative Energy Demand method. Processing one ton of waste PCBs involves significant energy consumption, particularly during the initial shredding phase, which results in substantial CO_2-eq emissions. The overall separation process was found to have a cumulative energy demand and CO_2-eq emissions of 1658.7 MJ and 99.9 kg, respectively. While the inertial and electrostatic separation stage was identified as the least environmentally impactful step, its energy intensity was only marginally lower – by less than 5% – compared to that of the initial shredding stage.

The contribution of each process step to the environmental impact is detailed in Fig. 3, using the Environmental Footprint 3.1 weighting method [28]. Size reduction steps, encompassing initial shredding, hammer milling, and fine grinding, are identified as significant contributors to the overall environmental performance. Among the various impact categories, *climate change* and *resource use, fossils* dominate the environmental performance, highlighting the critical influence of size reduction on the sustainability of the developed separation process. The size reduction of waste PCB composite material, predominantly composed of brittle ceramics, typically generates substantial airborne particles referred to as particulate matter (PM), which can pose signifi-



* Pre-treatment of the input may be required.

Fig. 1. Material flow documented for the developed separation process. The materials flow graph was adapted from [23], a study performed by the same authors as the present paper.

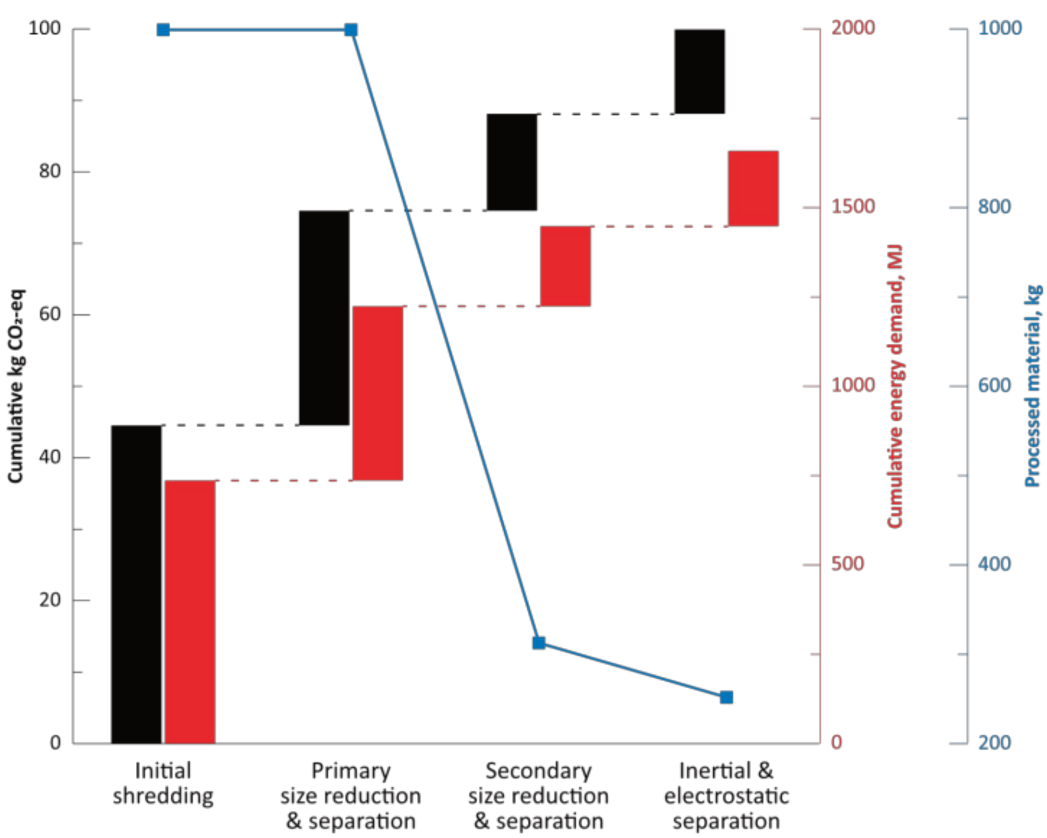


Fig. 2. Cumulative CO_2-eq and energy demand evolution throughout the mechanical separation process for treating one ton of waste PCBs, evaluated using the IPCC Global Warming Potential (20-year horizon) and Cumulative Energy Demand methods, respectively.

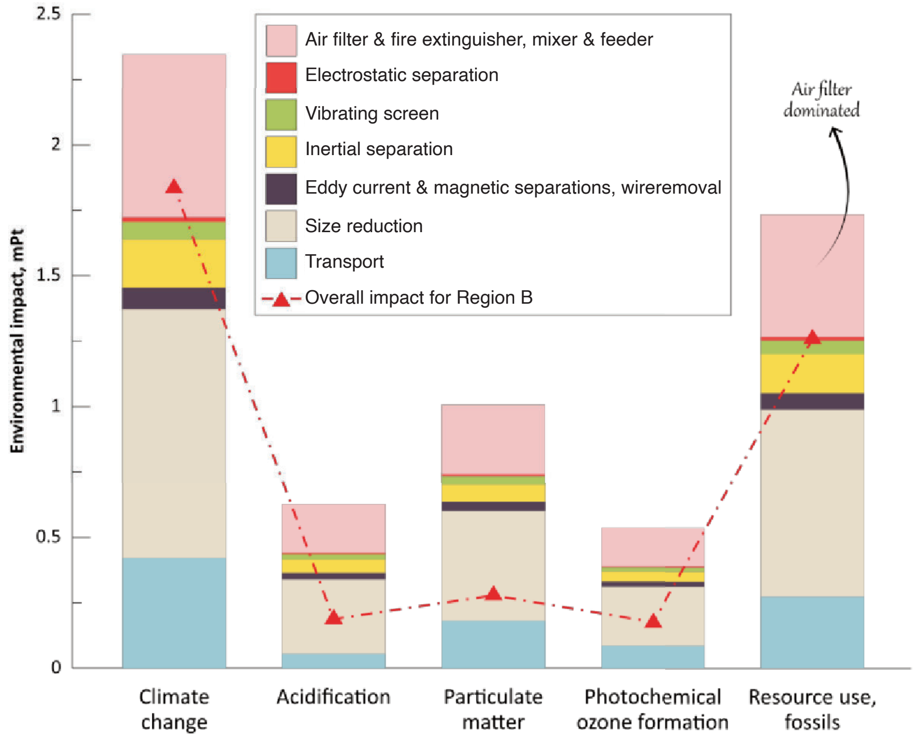


Fig. 3. Process impact contribution of the developed mechanical treatment for processing one ton of waste PCBs, calculated using the Environmental Footprint 3.1 weighting method, with sensitivity analysis (dashed red line). The analysis assumed that the developed process was employed in a region with lower dependence on fossil-based electricity. For simplicity, only impact categories with a contribution equal to or greater than photochemical ozone formation are shown.

cant risks to human health and thus plays a crucial role in determining the environmental performance of the process under study. Additionally, two other major contributors to the environmental impact are transportation, assumed to cover a distance of 80 km as per [35], and the air filter and fire extinguisher, with the latter's environmental effect primarily driven by high energy consumption.

The energy-intensive nature of the inertial separation considerably influenced the overall environmental impact of the developed separation process. This can be attributed to the substantial energy requirements for size reduction to a few millimeters, as well as the energy demands of the inertial separator (for comparison, inertial separation consumed 30 kWh/t, while the hammer mill consumed 6 kWh/t). Given that energy consumption during size reduction rises polynomially regardless of material type [36], even slight deviations from the size typically targeted in traditional WEEE mechanical treatment and separation can significantly affect the environmental impact. In contrast, processes such as eddy-current and magnetic separation have relatively minimal environmental impacts. It is worth noting that the presented LCA assumed that the process was carried out in Estonia, where the mechanical treatment was developed. Thus, electricity consumption was modeled using the Estonian electricity mix, which includes approximately 44.6% coal-based electricity generation, according to the International Energy Agency [37]. The sensitivity analysis, shown in Fig. 3 (dashed red line), considered a scenario where the mechanical treatment was implemented in Region B, with the electricity mix detailed in Table 2. As shown, the shift toward a less fossil fuel-dependent energy profile resulted in a noticeable reduction in environmental impact.

Figure 4 illustrates the cumulative survival deficit caused by particulate matter emissions (measured in disease incidence per kg of PM2.5 emitted) and cumulative fossil resource scarcity, both quantified using the Environmental Footprint 3.1 method, specifically the weighting approach. The analysis reveals that the initial shredding and primary size reduction and separation stages, which involve significant size reduction, are major contributors to both disease incidence and fossil resource depletion. Short-term exposure to particulate matter can exacerbate lung diseases, triggering asthma attacks and acute bronchitis, while also increasing susceptibility to respiratory infections. Additionally, in individuals with cardiovascular conditions, short-term exposure has been associated with an elevated risk of heart attacks [38].

Figure 5 illustrates the amount of materials liberated during the separation process, along with the price-weighted

Table 2. Comparison of the electricity profile for the reference scenario and Region B

Electricity mix	Fossil	Nuclear	Wind, solar, geothermal	Water	Biomass
Reference scenario	67%	16%	3%	4%	10%
Region B	60%	24%	11%	3%	2%

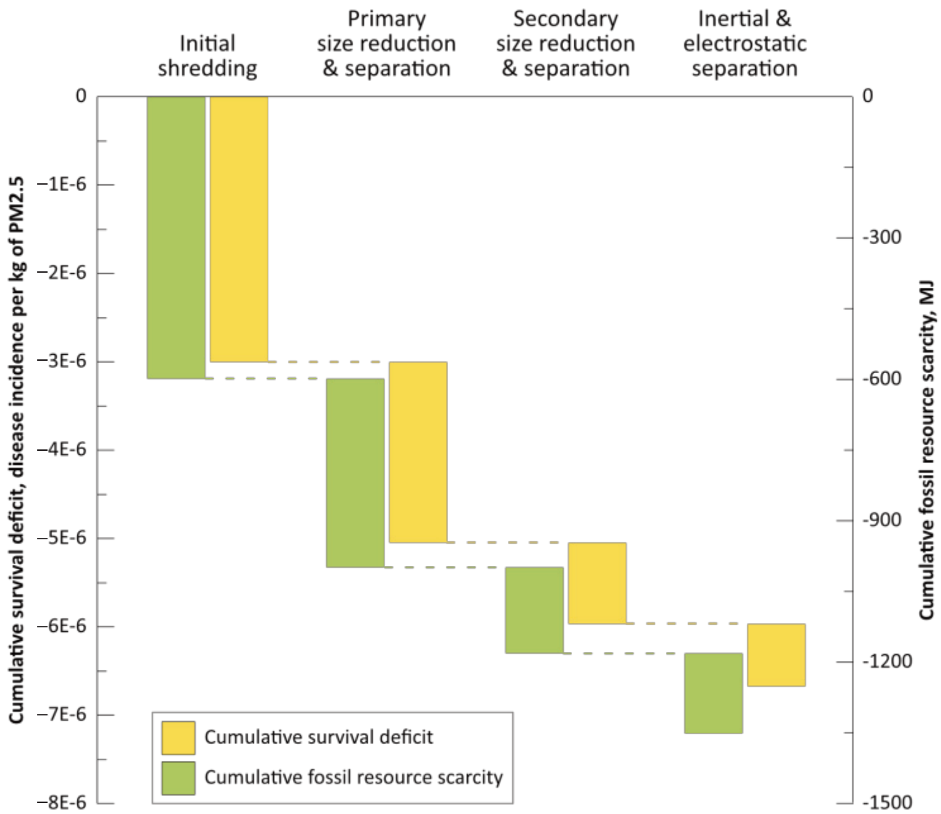


Fig. 4. Evolution of cumulative survival deficit and cumulative fossil resource scarcity during the developed mechanical treatment, analyzed using the Environmental Footprint 3.1 weighting method.

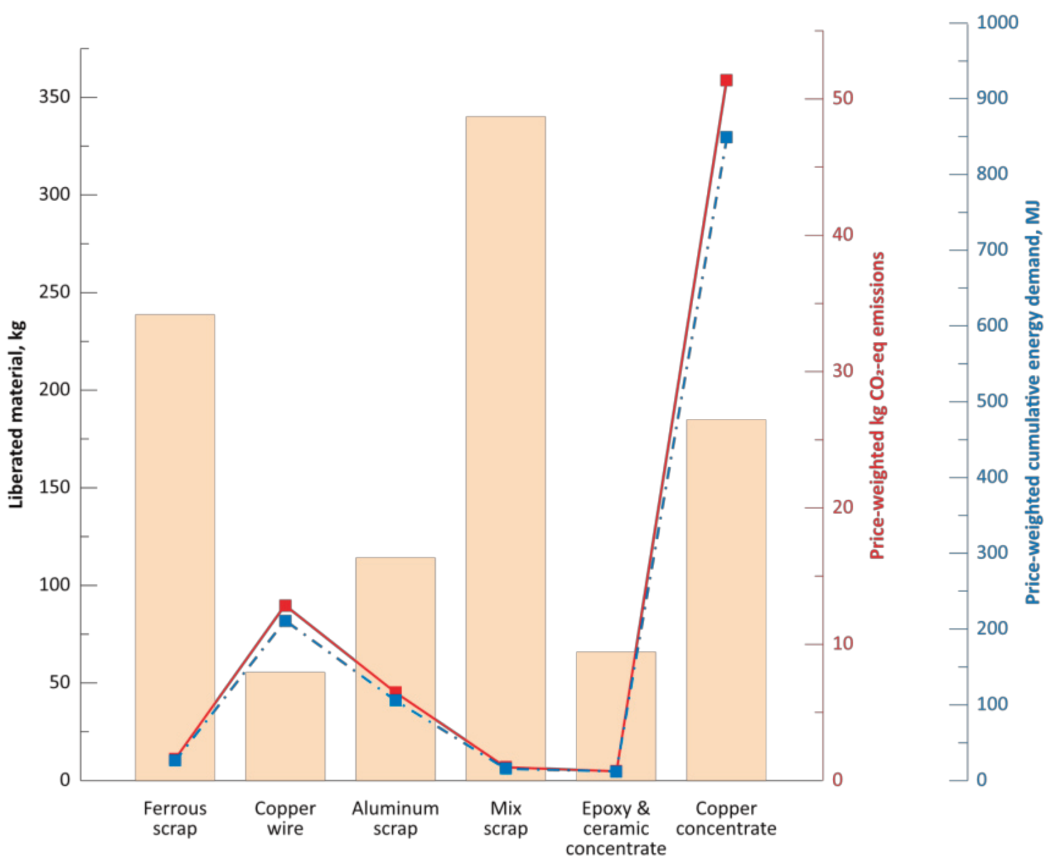


Fig. 5. Price-weighted CO_2-eq emissions and cumulative energy demand for each liberated fraction from waste PCB during the developed mechanical treatment process.

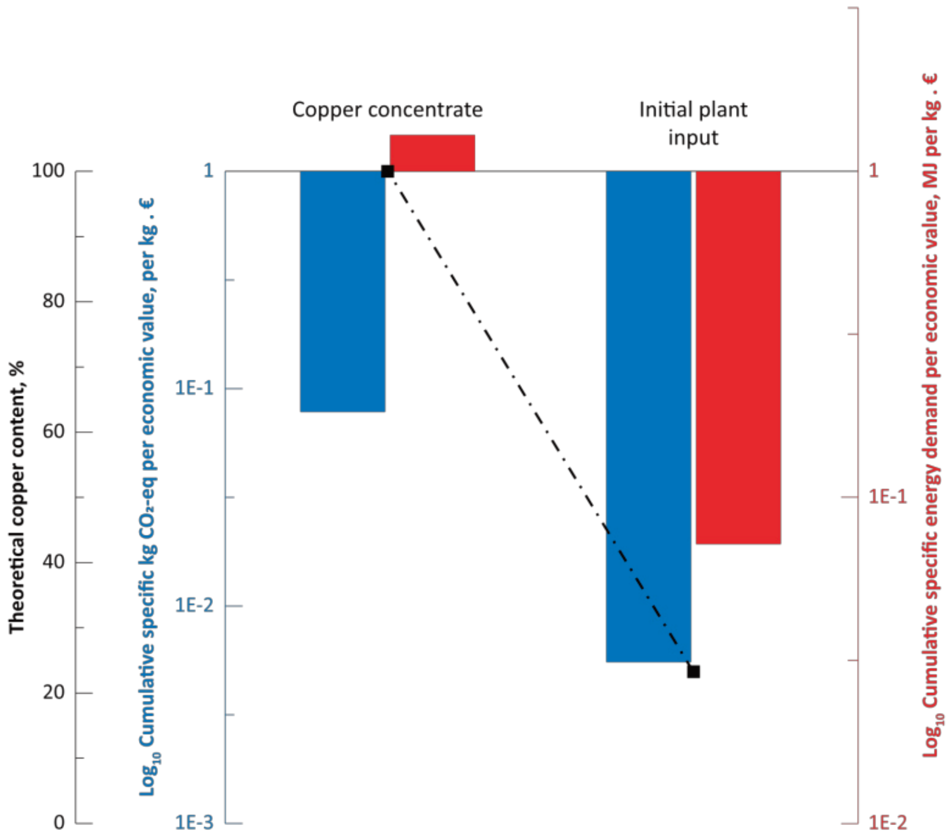


Fig. 6. Comparison of cumulative specific energy demand and cumulative specific CO_2-eq emissions for the copper concentrate and initial plant input, using the Cumulative Energy Demand and IPCC Global Warming Potential (20-year horizon) methods, respectively. The term "initial plant input" refers to the low-grade waste PCBs containing around 20% copper, with impacts predominantly influenced by transportation.

CO_2-eq emissions and price-weighted cumulative energy demand for the entire process. The prices for each liberated fraction were sourced from online trading websites [39–51]. Apparently, the price difference between the various liberated materials considerably influences the overall CO_2-eq and cumulative energy demand associated with each separated fraction. The primary goal of the developed process was to isolate epoxy and, consequently, generate a concentrated copper fraction for three key reasons: 1) to reduce bromine emissions during downstream metal recovery; 2) to enhance the efficiency of metals recovery in the subsequent pyrometallurgical process; and 3) to enable the valorization of epoxy through pyrolysis for the production of phenolic derivatives.

The findings presented in Fig. 5 offer valuable insights for decision-making. Notably, the majority of the copper separated from one ton of waste PCBs in the inertial and electrostatic separation stage showed noticeably high CO_2-eq and cumulative energy demand, amounting to 51.36 kg and 850.54 MJ per separated copper concentrate fraction (~185 kg), respectively. This translates to a price-weighted specific kg CO_2-eq of 0.28 kg and a price-weighted cumulative specific energy demand of 4.6 MJ per kg of copper concentrate. For the epoxy concentrate, the price-weighted specific CO_2-eq and cumulative energy demand were calculated at 0.01 kg and 0.18 MJ, respectively.

Figure 6 compares the cumulative specific CO_2-eq emissions and cumulative specific energy demand per unit of economic value for both the copper concentrate (assumed to be 100% copper) and initial plant input (low-grade waste PCBs with approximately 20% copper content). The results demonstrate that, throughout the process, the environmental impact per unit of economic gain for the copper concentrate evolves by more than one order of magnitude during the mechanical treatment, compared to initial plant input, the transportation of which emerges as the primary contributor to its environmental impact. The findings presented in Figs 5 and 6 underscore the importance of incorporating the downstream processes, particularly metals recovery, to fully assess the environmental performance of the proposed alternative throughout the entire recycling process chain.

Incorporating pyrolysis into downstream processes presents a promising opportunity to counterbalance the higher environmental impact of the developed mechanical treatment. Research has shown that transitioning from traditional waste PCB recycling methods, where epoxy resin is sacrificed during smelting – releasing toxic substances such as brominated dioxins, furans, and halogens – to advanced separation techniques, where the polymer fraction is isolated and utilized in pyrolysis, could reduce environmental impact by approximately 74% [52]. Pyrolysis is particularly advantageous, as it can transform epoxy resin into intermediate oil for chemical upgrading, producing high-purity benzene, toluene, ethylbenzene, xylenes, and concentrated monocyclic aromatic fractions [53]. Although initial investments in specialized pyrolysis infrastructure may be required for recycling epoxy resin, the long-term economic advantages are likely to outweigh these costs. Estimates suggest that a pyrolysis process utilizing polymers recycled from WEEE with yields exceeding 250 kg/h is economically viable [54]. Considering the annual waste PCB generation of approximately 400 000 tons in Europe [55] and around 5 million tons globally [56], this technology offers a potentially impact-reducing alternative. Broadening the scope of this study to integrate downstream impact-offsetting processes, such as those discussed earlier, could enhance the environmental and economic appeal of the proposed recycling approach. This transformative shift aligns seamlessly with the overarching objective of mitigating toxic emissions, such as brominated dioxins and halogens, and improving metals recovery efficiency, typically linked to conventional WEEE recycling approaches.

4. Conclusion

The separation plant piloting campaign provided evidence for high recovery yields of materials from waste PCBs. The recovery of aluminum and iron alone could evidently reduce the impact by cutting the amounts of iron and aluminum slags landfilled from metals refining [56]. The use of impact size reduction had a financially positive impact on plant performance by reducing the amounts of dust accumulated, lowering energy consumption (kWh/t), and offering relatively higher resilience (€/ton) compared to other methods introduced. The use of an inertial separator further reduced the costs compared to electrostatic and magnetic separators. The inertial separator was approved for use with the impact size reduction, as the selected critical size (d100 = 3.00 mm) was a good fit for inertial separation: the liberated metal and non-metal particles obtained form factors (surface differences) that allowed them to be more easily manipulated and hence separated. The overall use of all air- and electricity-dependent processes reduced dependence on chemicals and agents needed for running similar processes. This factor significantly lowers logistical costs and the costs for water and chemicals purification that may occur in competitive processes utilizing liquids as the medium for separation.

This study assessed the life cycle environmental impact of an advanced mechanical separation process for recycling printed circuit boards, using Environmental Footprint 3.1, IPCC Global Warming Potential, and Cumulative Energy Demand methods. The process successfully recovered a copper concentrate and an epoxy-rich fraction, which could reduce environmental impacts across the recycling chain. However, the process required 1658.7 MJ of energy and emitted 99.9 kg CO_2-eq per ton of PCBs processed, with energy-intensive size reduction identified as the primary contributor to these impacts. Sensitivity analysis showed that implementing the developed process in a region with a better electricity mix profile could noticeably reduce environmental impacts. The copper concentrate exhibited the highest environmental costs, with a price-weighted CO_2-eq of 0.28 kg and an energy demand of 4.6 MJ per kg of copper concentrate, highlighting the need for process optimization. Compared to unprocessed low-grade waste PCBs, the environmental impact per economic gain of copper concentrate evolved by about one order of magnitude over the developed mechanical treatment, further emphasizing the need to incorporate downstream materials recovery to fully capture the environmental performance of the proposed recycling chain.

Data availability statement

The data supporting this study are available upon reasonable request.

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Innovatiivse mehaanilise eraldamise keskkonnamõju analüüs jäätmetest trükkplaatide ringlussevõtuks

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Elektroonikajäätmete (e-jäätmete) kuhjumine tekitab üha suuremaid keskkonnaprobleeme, mida süvendab traditsiooniliste ringlussevõtumeetodite käigus vabanevate toksiliste broomiühendite emissioon. Trükkplaadid (PCB-d), mis on e-jäätmete oluline komponent, pakuvad ressursside taaskasutuse võimaluse tänu arenenud mehaanilistele eraldusmeetoditele. Uuring hindab välja töötatud PCB-de mehaanilise eraldusprotsessi keskkonnamõju, kasutades Environmental Footprint 3.1, IPCC globaalse soojenemispotentsiaali ja kumulatiivse energiavajaduse meetodeid. Analüüsitud protsessiga püütakse taastada rikastatud väljundeid, sealhulgas vaskkontsentraati ning epoksü- ja keraamikakontsentraati, eesmärgiga tõhustada metallide taaskasutust, toota fenoolseid ühendeid ja vähendada broomi emissiooni jäätmevoos. Tulemused näitavad, et 7–12% algsetest PCB-jäätmetest vabaneb epoksürikka kontsentraadina, mis koos vasefraktsiooniga näitab potentsiaali ringlussevõtuahela keskkonnamõju vähendamiseks. Protsess vajab siiski 1658,7 MJ kumulatiivset energiakulu ja tekitab 99,9 kg CO_2-ekvivalenti heitmeid ühe tonni PCB-de kohta. Suurim energiakulu tuleneb materjali suuruse vähendamisest millimeetri ulatuses, mis on vajalik inertsiaalseks ja elektrostaatiliseks eraldamiseks. Tundlikkuse analüüs tõi esile piirkondlike energiaprofiilide mõju: väiksem sõltuvus fossiilkütustel põhinevast elektrist vähendas märkimisväärselt keskkonnamõju. Uuring tõi välja taaskasutatud materjalide ebaproportsionaalse mõju: vaskkontsentraadi CO_2-ekv heitmete hinnapõhine koormus oli 0,28 kg ja energiavajadus 4,6 MJ ühe kilogrammi vabastatud vaskkontsentraadi kohta. Vaskkontsentraadi keskkonnamõju majandusliku kasu ühiku kohta suureneb protsessi jooksul suurusjärgu võrra võrreldes algse sisendiga, kusjuures transpordil on suurim osakaal. Tulemused rõhutavad arenenud mehaanilise eraldamise potentsiaali e-jäätmete ringlussevõtu tõhustamisel ning toovad esile edasised võimalused jätkusuutliku ringlussevõturaamistiku arendamiseks.