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Environmental assessment of noble metals recovery from e-waste: an ESCAPE and LCA-based comparative analysis towards design for sustainability

Alessandro Francini [a,*], Antonella Cornelio [b], Elza Bontempi [b], Angela Serpe [c,d], Anna Maria Ferrari [a,e], Paolo Neri [a], Roberto Rosa [a,e,f]

[a] Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Via G. Amendola 2, 42122, Reggio Emilia, Italy
[b] INSTM and Chemistry for Technologies Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38, Brescia, 25123, Italy
[c] Department of Civil and Environmental Engineering and Architecture (DICAAR), and Research Unit of INSTM, University of Cagliari, Via Marengo 2, 09123, Cagliari, Italy
[d] National Research Council of Italy, Institute of Environmental Geology and Geoengineering (CNR-IGAG), Via Marengo 2, 09123, Cagliari, Italy
[e] Interdepartmental Center for Applied Research and Services in the Advanced Mechanics and Motor Engineering Sector, InterMech - MO.RE, Piazzale Europa 1, 42124, Reggio Emilia, Italy
[f] Department of Economics, Science, Engineering and Design, University of San Marino Republic, Via Consiglio dei Sessanta 99, 47891, Dogana, Republic of San Marino

HIGHLIGHTS

- The LCA methodology was compared with the ESCAPE sustainability index.
- Focus on a hydrometallurgical method for recovering Cu, Ag and Au from e-waste.
- LCI modelling followed both mass- and economic-based allocation approaches.
- Monte Carlo uncertainty analysis was used to assess the reliability of LCA results.
- A combined LCA-ESCAPE tool is proposed for design for sustainability.

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ABSTRACT

The search for environmentally safer methods for recovering precious metals from electronic waste, through "urban mining", is gaining increasing research interest. Supporting these efforts requires simplified yet robust tools for sustainability assessment to guide the development of emerging technologies. The ESCAPE approach (Evaluation of Sustainability of material substitution using CArbon footPrint by a simplifiEd approach) provides a simplified method for comparing recovered or substitute materials with primary ones, focusing on carbon footprint and embodied energy as key metrics. This study evaluates the ESCAPE approach alongside the Life Cycle Assessment (LCA) methodology, applying both to an innovative hydrometallurgical method for extracting copper, silver, and gold from waste Random Access Memories (RAMs), tested on a laboratory scale. Results were used to assess the consistency between ESCAPE and LCA in identifying key parameters affecting the environmental impact of the recovery method and enabled a preliminary comparison based on available data for primary noble metals extraction. A dual mass and economic allocation approach was used for the LCA, and a Monte Carlo uncertainty simulation was applied to evaluate the robustness of the results. The findings reveal that the ESCAPE approach effectively identifies a significant portion of the system's potential environmental impacts, closely aligning with LCA outcomes. However, discrepancies emerge in specific environmental impact categories and when considering an economic allocation method. The here proposed conceptual framework aims to support the early-stage development of innovative and environmentally safer recycling methods, guiding them towards more sustainable and efficient configurations.

* Corresponding author.
E-mail address: alessandro.francini@unimore.it (A. Francini).

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1. Introduction

Environmental assessment is a critical procedure that ensures the potential environmental impacts of new processes, projects, or plans are thoroughly evaluated before they are implemented. This proactive approach helps prevent environmental harm and promotes sustainable development. Life Cycle Assessment (LCA) is a vital tool for systematically evaluating the environmental impacts of products and services across their entire lifecycle, from raw material extraction to disposal (Hellweg and Milà I Canals, 2014). Also, it may contribute to design for sustainability (D4S) of products and processes, as recommended by EU regulations (EU, 2024).

A peculiar case study of the role of environmental assessment for products and processes is the Waste Electrical and Electronic Equipment (WEEE) management.

In 2022, 62 billion kg of WEEE were produced globally according to the Global E-waste Monitor 2024, reflecting a growing trend that is expected to continue unhindered over the next decade (Baldé et al., 2024). Although the highest production rates are concentrated in high-income countries – particularly Europe, which generates 17.6 kg of e-waste per person (Baldé et al., 2024) – most of this waste is processed outside formal and controlled recycling streams in low- and lower-middle-income countries (Robinson, 2009; Shittu et al., 2021).

Commonly produced e-waste contains various heavy metals and toxic compounds (Kiddee et al., 2013). When not properly managed or lost to uncontrolled deposits, these substances can contaminate environmental matrices and pose significant risks to both human health and ecosystems (Abdullah et al., 2024; Chakraborty et al., 2022; Purchase et al., 2020). However, e-waste also presents a valuable opportunity as a profitable source of rare earth elements and precious materials, such as gold, silver, copper, platinum, and palladium, which are often found in higher concentrations than in mineral ores (Serpe et al., 2025; Shahabuddin et al., 2023; Wei et al., 2024).

Pyrometallurgical and hydrometallurgical methods are the primary techniques for recovering precious metals from WEEE (Islam et al., 2020; Li et al., 2019; Serpe, 2018). Pyrometallurgy involves high-temperature conditions, while hydrometallurgy uses specific chemical lixiviants (Wei et al., 2024). This latter is particularly valued for its ease of control and adaptability, as well as for the selectivity of the reactants and the multi-step nature (Serpe, 2018). However, traditional hydrometallurgical recovery of Noble Metals (NMs) from e-waste often relies on traditional, potentially harmful and aggressive methods, such as cyanidation and aqua regia (Islam et al., 2020). For this reason, current research efforts are focused on developing less environmentally demanding hydrometallurgical methods that align with green chemistry and engineering principles (Rigoldi et al., 2019).

Recovering noble metals through “urban mining” requires the implementation of recycling and recovery value chains. However, like any recycling system, these systems are not without potential environmental impacts. Therefore, it is essential to support these recovery strategies from the early stages with robust yet simplified sustainability metrics, to guide the design of processes towards more sustainable configurations by targeting the environmental hotspots.

Within this context, Bontempi (2017) proposed a simplified and versatile environmental assessment indicator, the ESCAPE index, based on just two metrics: embodied energy (EE) and carbon footprint (CF) of primary production. This dimensionless index was specifically designed to support low- and medium-low TRL recycling technologies in order to quantify the sustainability of recovered material compared to the raw material to be replaced, from which the ESCAPE acronym (Evaluation of Sustainability of material substitution using CArbon footPrint by a simplifiEd approach). The ability to conduct a preliminary screening by relying exclusively on a limited set of variables is crucial to ensure the adoption of sustainable practices, especially where the application of a complete Life Cycle Assessment study is not feasible (Ducoli et al., 2023).

The ESCAPE approach has been already applied to several case studies, starting from the reuse of stabilised municipal solid waste incineration fly ash as filler in polypropylene composites (Bontempi, 2017). The calculation of such index served also as a screening tool for the preliminary sustainability evaluation of 50 wastes-derived adsorbents (Ducoli et al., 2023), 33 technologies for lithium-ion batteries recovery (Fahimi et al., 2022a), 10 hydrometallurgical recycling processes for spent lithium-ion batteries (Fahimi et al., 2022b), 36 technologies for phosphorus recovery from sewage sludge ash (Fahimi et al., 2021) and a pilot scale plant for the recovery of metals from spent lithium-ion batteries (Cornelio et al., 2025). The approach has been validated several times against reference LCA databases, such as ecoinvent (Wernet et al., 2016), providing researchers with a versatile tool for assessing the level of sustainability of a newly developed or recovered material compared to a reference one, while relying on a robust and data-driven framework.

However, the ESCAPE approach has not yet been extensively compared to the Life Cycle Assessment methodology within the same system. LCA is indeed a well-established and standardised methodology for quantifying potential environmental impacts by adopting a holistic view of the system under study. Despite requiring a much deeper level of detail compared to existing simplified sustainability metrics, LCA can effectively highlight potential environmental impacts associated with emerging technologies at laboratory or pilot scale (Buyle et al., 2019; Ruini et al., 2023; Ungureanu et al., 2024). Moreover, the ability of the LCA approach to encompass several environmental impact categories facilitates the detection of potential burden-shifting, between different stages of the life-cycle or across impact categories, with the possibility to rely on normalised and weighted indicators for comparing alternative scenarios and material substitutions (Kralisch et al., 2015).

Within this context, LCA can serve as a benchmark for evaluating the outcomes of simplified sustainability assessment methods such as ESCAPE. By doing so, it becomes possible to identify their respective strengths and limitations, and to define the most appropriate application boundaries for their effective use. To partially address these aspects and to apply, for the first time, a direct comparison between the ESCAPE and LCA approaches, the present study investigates the same experimental system focused on the recovery of noble metals from Waste Printed Circuit Boards (WPCBs) (Rigoldi et al., 2019). As noted, the search for alternative, safer and less waste-producing hydrometallurgical pathways for precious metals recovery from WEEE is of high research interest (Serpe et al., 2015). In the analysed method, highly pure copper, silver and gold were recovered from WPCBs (i.e., Random Access Memories (RAMs)), by employing benign, selective, and recyclable reagents, under mild conditions (Rigoldi et al., 2019). This method is the starting point of an iterative experimental-environmental assessment (by ESCAPE) optimisation strategy carried out in the ongoing project SMaRT PCBs (Sustainable Materials Recycling Technology for Printed Circuit Boards) by involved partners, with the view to address and implement significant improvements to noble metals recovery from waste PCBs for a technical-economical-environmental technology transfer.

The ESCAPE index was first applied to this system to measure the sustainability of the recovered metal compared to the primary extraction from mineral resources, and to conduct a preliminary environmental screening of the lab-scale procedures. Subsequently, the LCA methodology was applied to the aforementioned system, using a mass and economic allocation based multi-output approach to model the Life Cycle Inventory, with the aim to provide a more detailed environmental profile of the recovery method under study. The LCA endpoint results for each recovered metal were then compared to those associated with the primary extraction of the same precious metals, establishing a comparison basis for the ESCAPE approach.

2. Methods

2.1. Case study: recovery of noble Metals from Waste Printed Circuit Boards

The dual ESCAPE-LCA approach was applied to a hydrometallurgical method for recovering copper, silver and gold from WPCBs using safe and recyclable reagents under mild conditions (Rigoldi et al., 2019; Serpe et al., 2015). A brief description of the experimental procedures is provided below.

Random Access Memory (RAM) modules (200 g) from mixed sources were subjected to mechanical milling for 24 h in a planetary ball mill (Retsch, 4-stage, 300 rpm) using stainless steel grinding media (6 mm diameter, 1.4 kg total mass). Carbsyn 110 (250 mL), a non-flammable milling aid, was added to facilitate particle size reduction. After milling, the slurry was sieved (4 mm mesh), the auxiliary fluid was recovered via distillation, and the milled material dried.

As fully detailed in Rigoldi et al. (2019), the initial metal composition of the sample, in terms of gold, copper, silver, palladium, and major base metals content, was determined by digesting five portions of the pre-treated RAM sample (1.5 g each) under microwaves (two-steps program lasting 10 + 20 min; T = 220 °C; MW power ≤1000 W; leaching mixture: 2 mL HNO_3 65 %, 6 mL HCl 37 % and 0.5 mL H_2O_2 30 %), then analysing the resulting solutions by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). In particular, the Cu, Ag, and Au contents were 15 ± 1 %, 0.04 ± 0.01 %, and 0.08 ± 0.03 %, respectively.

A 10 g portion of the pre-processed RAMs was treated with 300 mL of 3 M citric acid under reflux (100–120 °C, 48 h), generating hydrogen gas as a byproduct (Leaching 1). The resulting solid residue was filtered, washed, and dried.

The dried residue was stirred with aqueous ammonia (33 %, 15 mL) and ammonium sulphate (13.0 g) at ambient temperature. An iodine-sodium hydroxide solution (25 g I_2 in 150 mL of 1.5 M NaOH) was gradually added, which induced a colour shift to blue. After 48 h, the mixture was filtered, and the step was repeated until no further colour change occurred (Leaching 2). Silver iodide (AgI) precipitated as a yellow solid, and the resulting leaching solutions were collected for copper recovery.

The remaining solid was treated with sodium thiosulfate (0.06 M, 35 mL) at room temperature, and the leachate was filtered and collected for silver recovery (Leaching 3).

The final leaching step (Leaching 4) employed an iodine-potassium iodide solution (1.04 g I_2 + 3.68 g KI in 80 mL H_2O, 30 min at room temperature) to solubilise residual gold.

Copper recovery was carried out by cementation using zinc powder (5 g, 20 mesh). The resulting metallic Cu flakes were washed with diluted HCl, dried, and weighed, giving a recovery yield of 70 %. Silver and gold were recovered via electrowinning using a two-electrode system (Pt anode, Cu cathode) powered at 2.50 mV for 1 h without supporting electrolytes, resulting in recovery yields of 92 % for Ag and 65 % for Au (by weight).

2.2. ESCAPE index

ESCAPE approach is a simplified method designed to perform a preliminary sustainability analysis of materials, processes and technologies. It can be well applied at emerging technologies at lab or pilot scale allowing a rapid screening of environmental impacts to identify potential hotspots in the early design process and define informed decisions. Thanks to the evaluation of EE and CF it is possible to calculate the ESCAPE index, according to the following Equation (1):

$$\text{ESCAPE index} = \left[\log\left(\frac{EE_{raw}/\text{MJ}}{\text{kg}}\right) - \log\left(\frac{EE_{sub}/\text{MJ}}{\text{kg}}\right) + \log\left(CF_{raw}\right) - \log\left(CF_{sub}\right)\right]\cdot\frac{1}{2} \quad (1)$$

Where EE_{raw} and EE_{sub} are the EE related to the reference process (like raw material extraction – raw) and the proposed one (that may substitute the reference one – sub), respectively, expressed in MJ/kg; while CF_{raw} and CF_{sub} are the CF values of the reference material and the proposed one, respectively, expressed in $kgCO_{2eq}$/kg material. The obtained dimensionless index, generally ranging from −9 to +9, provides direct information about the sustainability of the process. A positive value suggests that the newly proposed process is more sustainable than the reference one, otherwise a negative value means that some improvements are necessary to increase the proposed process sustainability.

For reagents, EE and CF were provided from software like CES Selector (ecoinvent database, v3.9.1 (Wernet et al., 2016)) or Open LCA (Environmental Footprint database (European Commission, 2024)). The EE and CF values for each process are determined based on the instrument's power, the duration of the treatment, and an equivalence factor that reflects the energy mix of the country where the process takes place. Electricity was identified as the dominant source for heat generation. Since equivalence factors depend on the composition of the electricity mix – which differs from one country to another (Cornelio et al., 2025; Fahimi et al., 2022a) – European average factors were employed in this study. The adopted parameters characterise the transformation of electrical energy into either thermal or mechanical energy.

The data used to evaluate the ESCAPE index for the analysed NMs recovery method are available in the related Zenodo repository (Francini et al., 2025).

2.3. Life Cycle Assessment

A comprehensive environmental assessment of the experimental system under study was conducted using the Life Cycle Assessment methodology, in accordance with ISO 14040 (2006) and ISO 14044 (2006). Its constituting phases are detailed in the following sections.

2.3.1. Goal and Scope definition

This Life Cycle Assessment study aimed to evaluate the potential environmental impacts associated with the experimental method for recovering noble metals from waste RAMs, as detailed in Section 2.1. The LCA initially served to identify and characterise the process stages bearing the most significant environmental impacts. Additionally, aligned with the ESCAPE index definition, the LCA was used to gain deeper insights into whether recovering copper, silver, and gold from e-waste is more environmentally advantageous compared to their primary extraction from natural resources. To achieve this, the LCA outcomes for the system under study were compared with the ESCAPE results to evaluate the level of consistency between the two approaches and identify any potential discrepancies.

2.3.2. System, functional unit, and function of the system

The system under study focuses on the end-of-life treatment of waste RAMs, a specific sub-group of Waste Printed Circuit Boards. The functional unit is the total amount of milled RAMs sample undergoing the hydrometallurgical treatment under study, i.e., 10 g, as reported in

Rigoldi et al. (2019). The system boundaries include all activities described in Section 2.1, encompassing RAMs pretreatment (milling) and the four leaching steps to separate base metals, copper, silver, and gold from the solid sample. This is followed by three separate recovery steps for extracting Cu, Ag, and Au from the generated liquid leachates. The system boundaries also cover all necessary raw materials, transportation, electricity used during the experimental procedures, as well as the generated waste and emissions to the atmosphere. Fig. 1 provides a graphical representation of the processes and system boundaries included in this LCA.

2.3.3. Life cycle inventory (LCI) and life cycle impact assessment (LCIA)

The input data used in the LCA study were gathered directly from those involved in the experimental activities (Rigoldi et al., 2019; Serpe et al., 2015). Where primary data were unavailable, secondary data from similar studies or relevant literature were employed. For background processes, including chemicals production, transport, and electricity generation, the ecoinvent database (EID, v3.8) (Weidema et al., 2013; Wernet et al., 2016) served as the primary source of datasets and secondary data. In addition to the required material and energy inputs, the inventory also accounted for the equipment used and the treatment of waste generated during the leaching and NMs recovery stages.

Although LCA inherently provides a more comprehensive analysis than preliminary sustainability metrics, modelling choices were aligned, whenever possible, with those used in previous calculations of the ESCAPE index for this and other case studies (Ducoli et al., 2022), ensuring a consistent basis for comparison.

Electric energy consumption was estimated based on the power ratings and usage times of the equipment, unless specified otherwise, following methodologies used in similar lab-scale assessments (Rahman et al., 2022; Rosa et al., 2023; Ungureanu et al., 2024).

Materials and equipment transport was modelled based on an average distance of 100 km, assuming road freight transport using diesel EURO 6 lorries with two capacity ranges: 3.5–7.5 t and 16–32 t. The potential atmospheric emissions resulting from the chemicals used in the experimental activities were also considered. Particularly, the fugitive emissions were calculated as detailed in Equation (2) (Shine, 1996; US EPA, 2007). E_i represents the mass vented of the ith substance, χ_i its molar fraction in the liquid phase, γ_i the component activity coefficient (which equals 1 when Raoult's Law applies), P_i^{sat} its saturation vapour pressure (used for the considered range of concentration and temperature), MW_i its molecular weight, V_i the total volume of the substance (considered as the input amount of the liquid chemical), R the universal gas constant and T the absolute temperature.

$$E_i = \frac{V_i \cdot \chi_i \cdot \gamma_i \cdot P_i^{sat}}{R \cdot T} \cdot MW_i \tag{2}$$

For the liquid chemicals employed in workup, washing, and cleaning procedures, fugitive losses of 2 % were accounted for those with boiling points between 20 and 60 °C, and 1 % for those with boiling points between 60 and 120 °C (at 1 atm) (Jiménez-González et al., 2000).

99 % of each emitted substance was assumed to be retained by the aspiration system's activated carbon air filter. This applied only to the steps where the aspiration system was necessary for the experimental procedure and was therefore modelled accordingly.

Detailed life cycle inventories of the experimental recovery method

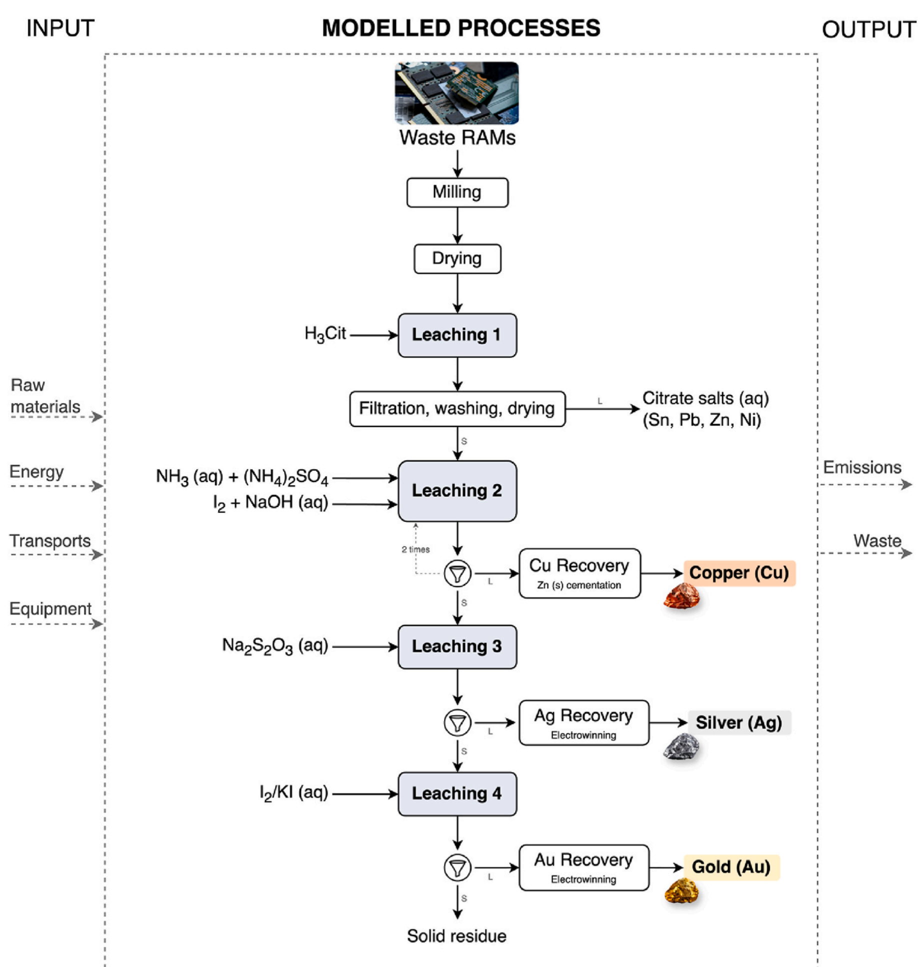

Fig. 1. System boundaries defined for the LCA of noble metals recovery from waste RAMs, according to the experimental procedure by Rigoldi et al. (2019).

under study are provided in the Supplementary data section and in the related Zenodo repository (Francini et al., 2025). Tables S2–S18 detail the inventories of the equipment used in the experimental activities, while Tables S20–S27 refer to the waste pretreatment, leaching and separation procedures for extracting copper, silver and gold from waste RAMs.

The experimental activities under study were modelled using the SimaPro software v9.5.0.1 (PRé Sustainability, 2023), following an attributional approach based on the APOS (Allocation at the Point of Substitution) system model, which expands product systems to avoid allocation in treatment stages, assigning responsibility for waste management between producers and the subsequent users who benefit from the treatment processes through the use of the valuable products generated (Wernet et al., 2016).

The hydrometallurgical method under investigation can be classified as a multifunctional process, as it simultaneously provides the end-of-life treatment for waste RAMs and enables the recovery of precious metals with high market demand. To address the multifunctionality of the process in line with the objective of the study, an allocation is necessary. According to ISO standards, when allocation cannot be avoided, it should reflect the physical relationship between the environmental burdens and the process's multiple functions (Ekvall and Finnveden, 2001; ISO 14044, 2006).

In metallurgical activities and precious metal recovery processes, the economic value of the output materials plays a crucial role in determining profitability and, consequently, the overall viability of the treatment (Guinée et al., 2004; Santero and Hendry, 2016; Rigoldi et al., 2019). This influence is often greater than the amount of metals that can potentially be recovered. Therefore, to properly account for the quality of the recovered materials (i.e., their economic value) an economic allocation approach is recommended when partitioning material and energy flows. In a previous LCA study by Bigum et al. (2012), investigating the recovery of Cu, Ag, Au, Al, Fe, Ni, and Pd from high-grade WEEE, no definitive solution to the allocation issue was found, leading the authors to apply both mass and economic allocation.

In the present case study, Life Cycle Assessment results served also as a point of comparison with the ESCAPE index, which was originally defined on a mass basis (Bontempi, 2017). Therefore, to better understand the influence of different allocation methods on the overall results, both mass and economic allocation approaches were applied to this LCA. Specifically, the system's function (e.g., waste treatment) was included in the allocation scheme together with the recovered outputs, as described in Guinée et al. (2021) and Doka (2023). The criteria adopted for mass and economic allocation are summarised in Table 1. For economic allocation, the market values of gold, silver, and other metals were averaged over a three-year period (2022–2024) to mitigate the effects of price volatility on the recovered metal revenues.

To assess the influence of the adopted methodological choice on the results, two sensitivity analyses employing different modelling approaches were also performed (see Section 4).

The global-scale oriented ReCiPe 2016 method was used for the life cycle impact assessment (LCIA) phase. It was applied at both midpoint and endpoint levels, adopting a hierarchist (H) perspective (Huijbregts et al., 2017). At the endpoint level, results are expressed as a dimensionless environmental score (Pt), obtained through normalisation and weighting of the damage assessment results. Specifically, global normalisation factors from the year 2010, as defined by the ReCiPe 2016 method, were applied. The weighting factors were sourced from the Ecoindicator 99 method, using the average ("A") weighting set. These weighting factors assign weights of 400 for both human health and ecosystems, and 200 for resource damage categories (Goedkoop and Spriensma, 2001).

3. Results and discussion

3.1. ESCAPE index results

For the evaluation of ESCAPE indices for Au, Cu and Ag recovery, data were normalised to 1 kg. According to the processes described by Rigoldi et al. (2019) and Serpe et al. (2015), the information on the power of instruments used for each process were found from technical data sheets, or if not available data were provided from literature (Ducoli et al., 2022).

Moreover, certain assumptions were made concerning the EE and CF values of some reagents used. RAM is considered a waste material, and its EE and CF values are negligible. For Carbsyn, since it can be fully recovered at the end of the process, its contribution to both parameters is considered negligible. Regarding $Na_2S_2O_3$, I_2, and KI, the Environmental Footprint database did not provide EE and CF values. Values were obtained by searching in the literature the processes of extraction/production of the reagent considered, and then thanks to the Environmental Footprint database, the values of the semi-product immediately preceding the reagent in consideration were found. Table 2 reports the EE and CF values of reagents used in the described process (Rigoldi et al., 2019) and the EE and CF values of Cu, Ag and Au, derived from the Environmental Footprint database and used as a reference for EE_{raw} and CF_{raw}.

The EE and CF values calculated for each step are reported in Table 3.

The greatest contribution is associated with the first leaching due to the high value of EE and CF associated with citric acid, 74.4 MJ/kg and 3.1 $kgCO_{2eq}$/kg, respectively, and the duration of treatment (48 h). It can be observed that these values are so high because the process is still at a laboratory scale, and thus it may be optimised, reducing its impact, for example recovering the citric acid from food waste. The second in term of impact is Leaching 2 due to the I_2 and long treatment time (mainly related to a prolonged use of an aspiration system).

Fig. 2 reports the relative contribution of processes (mechanical and thermal), chemicals and water on the EE and CF values. The most interesting results concern Leaching 1 and 2 where it is clear how the chemicals affect the process despite the longtime of treatment. In nearly all treatments, the contribution of water is negligible; however, in Leaching 3 it becomes more relevant, particularly for CF values, due to the comparatively lower contributions of processes and chemicals to the overall CF and EE values in that step.

Table 1
Input data for mass and economic allocation percentages.

		E-waste treatment	Recovered metals		
			Copper (Cu)	Silver (Ag)	Gold (Au)
Amount (kg)		1E-2	1.05E-3	3.68E-6	5.20E-6
Mass allocation	Allocation percentage (%)	90.43	9.49	0.033	0.047
Economic allocation	Cost (€/kg)	9.50E-2[a]	8.23[b]	7.34E+02[c]	6.12E+04[d]
	Allocation percentage (%)	0.29	2.61	0.82	96.28

[a] The system's function was economically allocated based on a reference cost for WPCBs treatment ("Consorzio ecoR'it," 2010).
[b] The reported value represents the average market price of copper over the years 2022, 2023, and 2024 (The World Bank, 2025).
[c] The reported value represents the average market price of silver over the years 2022, 2023, and 2024 (The World Bank, 2025).
[d] The reported value represents the average market price of gold over the years 2022, 2023, and 2024 (The World Bank, 2025).

Table 2
Embodied Energy (EE) and Carbon Footprint (CF) values of the reagents used in the recovery process of Au, Ag and Cu from waste RAMs.

Chemical reagents	EE (MJ/kg)	CF ($kgCO_{2eq}/kg$)
Tap water	0.005	0.0003
Citric acid H_3cit	74.4	3.1
Ammonia NH_3	40.6	2.2
Ammonium sulphate $(NH_4)_2SO_4$	6.2	0.5
Sodium hydroxide NaOH	12.5	3.2
Sodium thiosulphate $Na_2S_2O_3$	12.2	0.03
Hydrochloric acid HCl	11.8	0.7
Diiodine I_2	36.1	3.5
Potassium iodide KI	27.4	1.9
Zinc Zn	27.2	1.6
Acetone C_3H_6O	53.3	1.9
Copper Cu	90	3.9
Silver Ag	4693	318
Gold Au	645299	61599

Table 3
Embodied Energy (EE) and Carbon Footprint (CF) calculated for each step.

	EE (MJ/kg)	**CF** ($kgCO_{2eq}/kg$)
Milling and sieving	15	0.74
Leaching 1	1549	64
Leaching 2	226	25
Leaching 3	0.49	0.005
Leaching 4	14	1.1
Cu recovery	16	1.4
Ag recovery	0.07	0.003
Au recovery	0.07	0.003

Once evaluated the EE and CF for all the process phases, it is possible to calculate the EE_{sub} and CF_{sub} for Au, Ag and Cu, according to their percentage in the RAM sample, 0.08 %, 0.04 % and 15 %, respectively, and their recovery percentage, 65 %, 92 % and 70 %, respectively. Applying Equation (1), ESCAPE indices for Au, Ag and Cu were calculated and reported in Table 4.

ESCAPE index values are strongly influenced by the percentage of the considered material in the sample and its recovery percentage. Furthermore, they strictly depend on EE_{raw} and CF_{raw} related to the reference processes that are established on an industrial scale, not directly comparable to a small still not engineered laboratory process. Nonetheless, for a preliminary but significant indication, the calculated ESCAPE indices of Cu and Ag are negative while the ESCAPE index of Au is positive. This means that, besides the low amount of Au in RAM sample, the proposed extraction process seems to be more sustainable than the primary extraction. This result is also related to the high value of EE and CF associated with the raw material extraction.

Due to its ease of application, the ESCAPE method serves as a pre-screening phase aimed at identifying critical points within a process and exploring alternative solutions to enhance the sustainability of the proposed process. For this reason, despite the negative ESCAPE index values for Cu and Ag, these values can guide the identification of areas requiring improvements. Despite the higher amount of Cu in the RAM sample and the 70 % recovery, the negative value of the ESCAPE index is

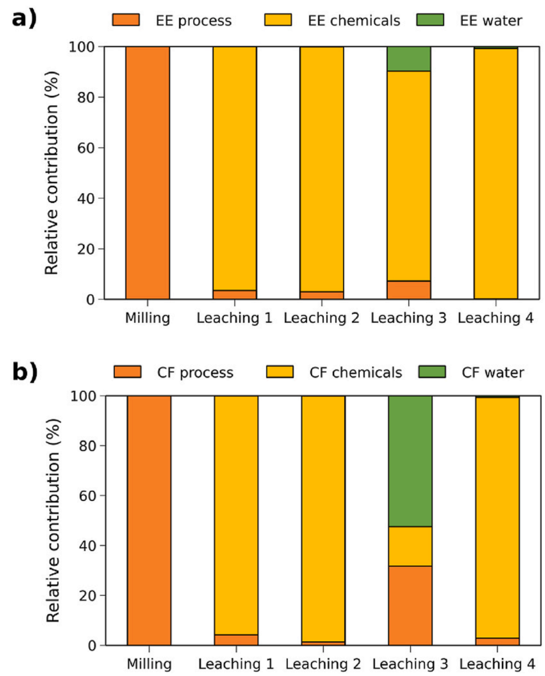

Fig. 2. Relative contribute of **a)** Embodied Energy (EE) and **b)** Carbon Footprint (CF).

Table 4
ESCAPE indices for Cu, Ag and Au calculated according to Equation (1).

	ESCAPE index
Cu	−2.3
Ag	−0.4
Au	1.7

also related to the lower value of EE and CF for raw material extraction compared to the ones associated with Au (see Table 2). Moreover, although the ESCAPE index value for Ag is slightly negative, this is highly encouraging, as minor improvements can significantly enhance the sustainability of its recovery.

In general, the calculation of the ESCAPE index considers the EE and CF of primary production. I_2 and KI can be recovered at the end of the process and reused, a strategy that enhances the sustainability of the system. The reutilisation of these reagents reduces the demand for raw materials, thereby mitigating the environmental impact associated with their production. Given the relative scarcity and economic value of iodine, its efficient recovery contributes to resource conservation and cost reduction.

3.2. Life Cycle Assessment results

The midpoint environmental impact results associated with the recovery of Cu, Ag, and Au from 1 kg of waste RAMs are summarised in Table 5, referred to both mass and economic allocation. A detailed analysis of the major contributors to each environmental impact category is available in the Supplementary data section.

As shown in Table 5, the midpoint results for economic allocation are consistently lower. This variation is due to the system's function being allocated at only 0.29 % under economic allocation, compared to 90.4 % under mass allocation, as reported in Table 1.

However, the relative contributions of each treatment step to these impacts are consistent. These are visually presented in Fig. 3, showing the relative contribution of each phase to the impacts across 18

Table 5
Midpoint environmental impact results associated with the treatment of 1 kg of waste RAMs for noble metals recovery (ReCiPe, 2016 Midpoint, H).

Impact category	**Unit**	**Noble Metals Recovery from 1 kg of waste RAMs**	
		Mass allocation	Economic allocation
Global warming	kg CO_2 eq	1.21E+03	3.85E+00
Stratospheric ozone depletion	kg CFC11 eq	8.21E-04	2.61E-06
Ionizing radiation	kBq Co-60 eq	1.05E+02	3.35E-01
Ozone formation, Human health	kg NO_x eq	2.06E+00	6.54E-03
Fine particulate matter formation	kg PM2.5 eq	1.49E+00	4.75E-03
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.11E+00	6.69E-03
Terrestrial acidification	kg SO2 eq	4.10E+00	1.30E-02
Freshwater eutrophication	kg P eq	4.05E-01	1.29E-03
Marine eutrophication	kg N eq	5.58E-02	1.77E-04
Terrestrial ecotoxicity	kg 1,4-DCB	6.88E+03	2.19E+01
Freshwater ecotoxicity	kg 1,4-DCB	1.04E+02	3.30E-01
Marine ecotoxicity	kg 1,4-DCB	1.33E+02	4.22E-01
Human carcinogenic toxicity	kg 1,4-DCB	1.61E+02	5.10E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.36E+03	4.32E+00
Land use	m^2a crop eq	4.66E+01	1.48E-01
Mineral resource scarcity	kg Cu eq	4.10E+01	1.30E-01
Fossil resource scarcity	kg oil eq	3.09E+02	9.82E-01
Water consumption	m^3	2.12E+01	6.72E-02

environmental categories, with each column summing to 100 %.

The first and second leaching steps determine the highest environmental burdens. Specifically, Leaching 1 exhibits the highest relative impacts in several categories, including stratospheric ozone depletion (64.4 %), ionizing radiation (62.7 %), marine eutrophication (63.4 %), land use (65.7 %), and water consumption (64.4 %). These impacts are primarily driven by the electricity required to operate the equipment throughout the reaction (e.g., heating plate, recirculating chiller), as well as the consumption of citric acid. Leaching 2, on the other hand, contributes most to the human carcinogenic toxicity (69.6 %) and mineral resource scarcity (86.5 %) categories. These impacts are respectively attributed to the operation of the aspiration system (and the associated life cycle), and the consumption of iodine. Notably, iodine recovery can be effectively implemented by processing the leachate solution collected after the second leaching step. By reinserting part of the recovered iodine at the beginning of the process, the overall consumption of raw iodine could be minimized. Although this recovery step was not included in the current ESCAPE-LCA sustainability evaluation, its potential integration could be further analysed to assess its effectiveness in reducing environmental impact, particularly in the mineral resource scarcity category. Furthermore, a closed-vessel configuration with an internal recirculation of fumes would prevent, at an industrial scale, the economic and environmental impact related to the use of a fume hood.

By following midpoint-to-endpoint damage pathways, the obtained environmental impact results can be translated into potential damage across three main areas of protection: human health, ecosystems, and resources. These endpoint results can then be normalised and weighted to produce a dimensionless indicator which represents the overall magnitude of the environmental load, expressed in points (Pt).

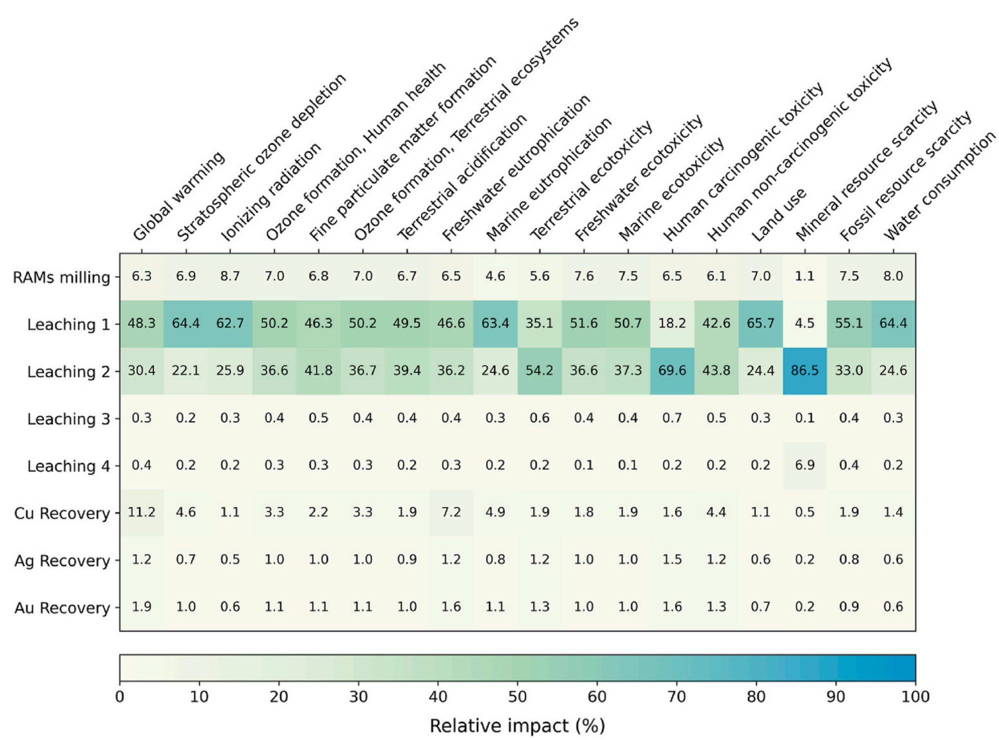

Fig. 3. Midpoint environmental impact results associated with the end-of-life treatment of 1 kg of waste RAMs, expressed as relative percentage contributions to 18 environmental categories (ReCiPe, 2016 Midpoint, H).

Table 6
Single score results (ReCiPe, 2016 Endpoint, H/A) associated with the end-of-life treatment of 1 kg of waste RAMs for noble metals recovery, for both mass and economic allocation.

	Single score environmental damage (Pt)	
	Mass allocation	Economic allocation
Human Health	4.91E+01	1.56E-01
Ecosystems	1.50E+00	4.75E-03
Resources	7.02E-01	2.23E-03
Total	**5.13E+01**	**1.63E-01**

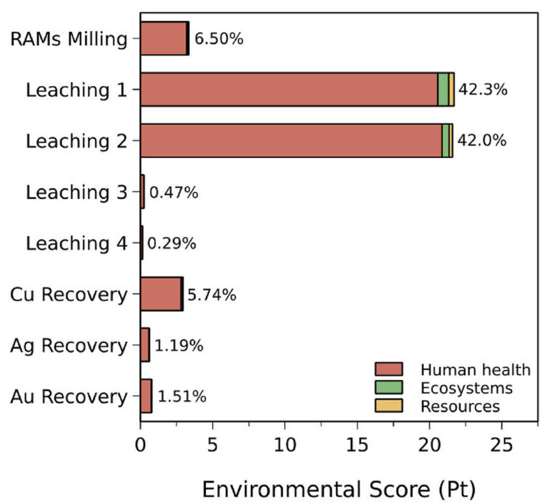

Fig. 4. Single score results (ReCiPe, 2016 Endpoint, H/A) associated with the treatment of 1 kg of waste RAMs for NMs recovery, when adopting a mass allocation approach.

The normalised and weighted single score endpoint results associated with the recovery of NMs from 1 kg of waste RAMs, are detailed in Table 6, for both mass and economic allocation.

The analysed lab-scale recovery method results in a total environmental load of 51.3 Pt for mass allocation and 0.163 Pt for economic allocation. In both cases, 95.7 % of the total damage is attributed to the human health category, followed by ecosystems at 2.91 % and resources at 1.37 %.

The relative contributions to the overall environmental score are illustrated in Fig. 4 for mass allocation and in Fig. S1 for economic allocation.

As already hinted by midpoint environmental impact results, the first and second leaching steps contribute nearly equally to the overall impact, accounting for 42.3 % and 42.0 %, respectively. Marginal contributions are observed from RAMs pretreatment (6.50 %) and copper recovery (5.74 %). The underlying reasons are evident when examining the major contributions to the environmental endpoint results of Leaching 1 and 2, reported in Fig. 5. A detailed analysis of the first leaching step shows that the highest contributions are mainly associated with the consumption of electric energy required to heat the reaction to 110 °C for 48 h (76.7 %). Additionally, a smaller contribution (11.5 %) is linked to the employed chemicals, mainly due to citric acid consumption. For Leaching 2, the primary contributions are attributed to the use of the aspiration system (68.1 %) and the electric energy consumption needed for the reaction and to power the aspiration system for the entire 48-h procedure (26.5 %). Since electricity consumption represented one of the main energy sources for the laboratory-scale process and a significant contributor to the environmental burden, Table S28 provides, for clarity, the power demand, the operating time and the total electricity consumption of each piece of equipment and auxiliary system considered in the LCA model.

3.3. ESCAPE-LCA comparison

To compare the LCA results with the ESCAPE index, the environmental burdens associated with the proposed hydrometallurgical recovery method were analysed together with those of the primary extraction process. The inventories describing the primary extraction and the refining of copper (Cu), silver (Ag), and gold (Au) were derived from the ecoinvent database (v3.8). The selected datasets are respectively “Copper, cathode {GLO}| electrorefining of copper, anode | APOS, U″, “Silver {RoW}| gold-silver mine operation with refinery | APOS, U″, and “Gold {RoW}| gold-silver mine operation with refinery | APOS, U”.

The comparisons were made at midpoint and endpoint levels, evaluating the recovery of 1 kg of metal using both mass and economic allocation, together with the primary extraction of 1 kg of each metal. Midpoint results are detailed in Table S29 and graphically summarised in Fig. 6 as a function of the 18 environmental impact categories of the ReCiPe 2016 method. It should be remarked that, as for the ESCAPE approach, data related to the primary extraction refer to well established industrial scale processes applied on a specific virgin natural feedstock for each metal. For this reason, caution should be used when comparing them with a small scale, not engineered process working on a waste stream containing all these valued metals together. Nevertheless, the tested approach seemed robust in comparing ESCAPE vs LCA outputs, given comparable inputs, and, consequently, in designing experimental corrections on the innovative method to pursue the highest sustainability as possible.

Based on the above, independently of the allocation considered, the recovery of copper from WPCBs shows significantly higher environmental impacts compared to the primary extraction in nearly all

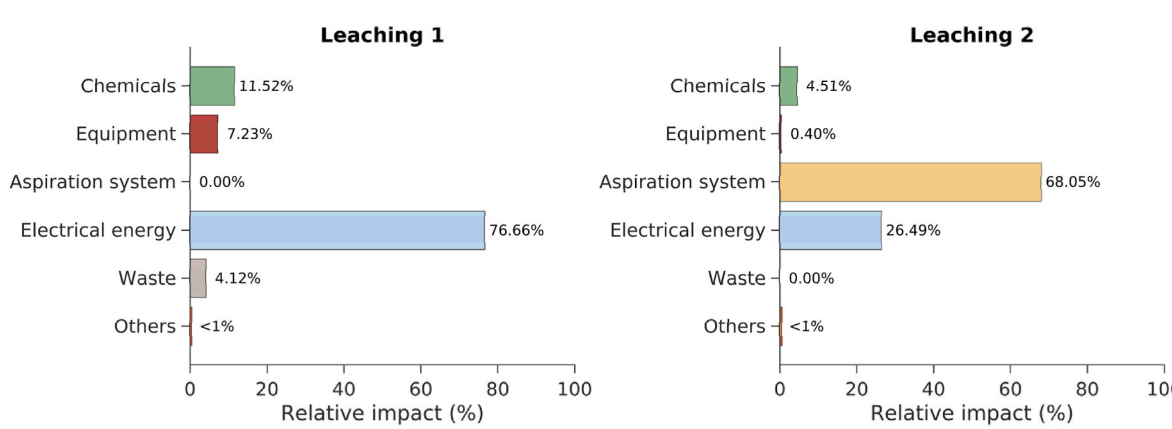

Fig. 5. Relative environmental impacts reported as percentages to the single score (ReCiPe, 2016 Endpoint, H/A) associated with Leaching 1 and Leaching 2 stages.

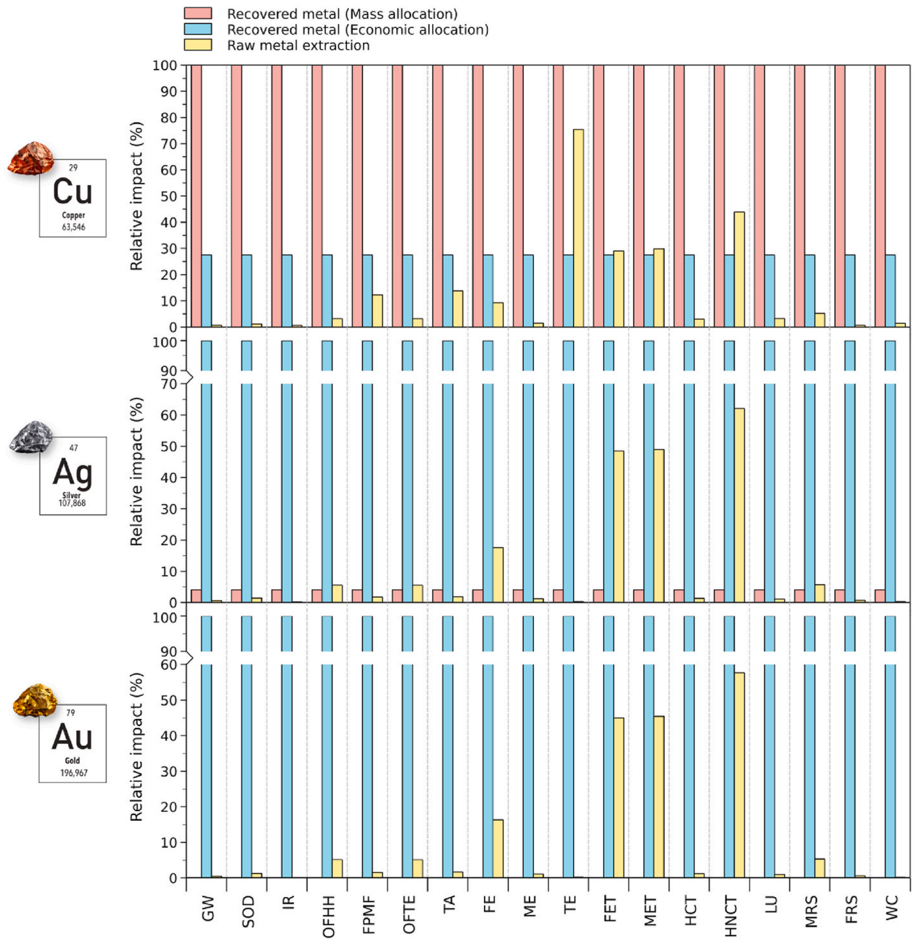

Fig. 6. Relative environmental impacts calculated at the midpoint level (ReCiPe, 2016; H) for metal recovery with mass allocation (red bars), metal recovery with economic allocation (blue bars), and raw metal extraction (yellow bars), for each noble metal considered in the study (Cu, Ag, Au). The following environmental impact categories were considered: global warming (GW, kg CO_2 eq), stratospheric ozone depletion (SOD, kg CFC-11 eq), ionizing radiation (IR, kBq Co-60 eq), ozone formation-human health (OFHH, kg NO_x eq), fine particulate matter formation (FPMF, kg $PM_{2.5}$ eq), ozone formation-terrestrial ecosystems (OFTE, kg NO_x eq), terrestrial acidification (TA, kg SO_2 eq), freshwater eutrophication (FE, kg P eq), marine eutrophication (ME, kg N eq), terrestrial ecotoxicity (TE, kg 1,4-DCB), freshwater ecotoxicity (FET, kg 1,4-DCB), marine ecotoxicity (MET, kg 1,4-DCB), human carcinogenic toxicity (HCT, kg 1,4-DCB), human non-carcinogenic toxicity (HNCT, kg 1,4-DCB), land use (LU, m2a crop eq), mineral resource scarcity (MRS, kg Cu eq), fossil resource scarcity (FRS, kg oil eq), and water consumption (WC, m^3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

categories, except for terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity. In these specific categories, copper recovery via economic allocation results in lower impacts than the primary extraction from mineral ores.

Regarding silver, the extraction and refining processes for this noble metal are associated with lower environmental impacts than the proposed recovery method in all categories except for ozone formation-human health, ozone formation-terrestrial ecosystems, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, and mineral resource scarcity. In these categories, when assuming a mass allocation, silver recovery from waste RAMs proves to be more sustainable than the primary extraction.

When adopting a mass allocation for gold recovery, the potential environmental impacts are consistently lower in all categories compared to the extraction from natural ores. On the other hand, for economic allocation, the recovery of gold from waste RAMs is associated with the highest environmental impacts. This is primarily due to gold's high market price, which ultimately results in a high allocation percentage for the metal recovered at the end of the procedure (i.e., 96.3 %).

The endpoint results calculated for the recovery of noble metals and the primary extraction are summarised in Table 7 and visually presented in Fig. S2 as relative percentages.

Table 7
Endpoint single score results (ReCiPe, 2016; H/A) associated with the recovery of 1 kg of copper, silver and gold and the primary extraction of 1 kg of each raw metal.

Damage category	Unit	Copper			Silver			Gold		
		Recovery		Primary extraction	Recovery		Primary extraction	Recovery		Primary extraction
		Mass allocation	*Economic allocation*		*Mass allocation*	*Economic allocation*		*Mass allocation*	*Economic allocation*	
Human health	Pt	4.91E+01	1.35E+01	4.60E+00	4.91E+01	1.21E+03	9.12E+01	4.91E+01	1.01E+05	7.06E+03
Ecosystems	Pt	1.50E+00	4.12E-01	7.52E-02	1.50E+00	3.67E+01	9.67E-01	1.50E+00	3.06E+03	7.49E+01
Resources	Pt	7.02E-01	1.93E-01	6.92E-03	7.02E-01	1.72E+01	2.28E-01	7.02E-01	1.44E+03	1.77E+01
Total	**Pt**	**5.13E+01**	**1.41E+01**	**4.69E+00**	**5.13E+01**	**1.26E+03**	**9.24E+01**	**5.13E+01**	**1.05E+05**	**7.16E+03**

Copper recovery exhibits a higher environmental score compared to its primary extraction, regardless of whether mass or economic allocation is applied. In contrast, silver recovery under mass allocation results in a slightly lower environmental load than extraction from natural ores, but remains higher when using economic allocation. For gold, recovery proves more environmentally favourable than the raw metal extraction when considering a mass allocation, while economic allocation results in greater environmental burdens.

To quantitatively represent the level of agreement with the ESCAPE index, LCA single score results were used to calculate two indices, defined as follows (Equations 3-4).

$$\text{LCA} - \text{MA index} = \log\left(ES_{\text{primary}}\right) - \log\left(ES_{\text{recovered,MA}}\right) \quad (3)$$

Where:

ES_{primary} (Pt) is the endpoint environmental score associated with the extraction of the primary metal from natural resources.

$ES_{\text{recovered, MA}}$ (Pt) is the endpoint environmental score associated with the recovery of the secondary metal from waste (i.e., waste RAMs), when considering a mass allocation approach.

$$\text{LCA} - \text{EA index} = \log\left(ES_{\text{primary}}\right) - \log\left(ES_{\text{recovered,EA}}\right) \quad (4)$$

Where:

ES_{primary} (Pt) is the endpoint environmental score associated with the extraction of the (primary) metal from natural resources.

$ES_{\text{recovered, EA}}$ (Pt) is the endpoint environmental score associated with the recovery of the (secondary) metal from waste (i.e., waste RAMs), when adopting an economic allocation approach.

The LCA indices are presented on a logarithmic scale to account for significant variations in single score results and to facilitate comparison with the ESCAPE index, which is defined using the same scale. These are positive (>0) when the recovered metal is associated with a lower environmental load than the primary extraction, and negative (<0) when the primary extraction determines a lower environmental burden compared to the secondary metal.

A brief comparative description of the LCA and ESCAPE indices is provided in Table 8, while the calculated values for copper, silver and gold are shown in Fig. 7.

The LCA mass-based indices for copper and gold are consistent with the ESCAPE index results. The proposed experimental recovery method proves to be less environmentally sustainable for copper recovery, while for gold it offers an environmentally preferable alternative to primary extraction from natural resources. In contrast, the LCA mass-based index for silver, just above zero, suggests that recovering silver from waste RAMs is associated with lower environmental burdens than extracting it from mineral ores.

Regarding the economic-based LCA scores, copper and silver align with the ESCAPE indices (negative values), whereas gold recovery from e-waste appears less sustainable than raw material extraction. This latter finding is primarily due to gold's high market price, leading to a high allocation percentage (i.e., 96.3 %) for the total gold recovered. As said, it is worth noting that these values are derived from an early-stage, laboratory-scale recovery method, in contrast to well-established industrial reclamation processes. Future upscaling of the proposed experimental recovery method is likely to lower the associated environmental impacts through process optimisations and improvements in material and energy efficiency (Piccinno et al., 2016), potentially leading to positive changes in the ESCAPE and LCA indices for the recovered metals. Consequently, the already favourable values observed for the ESCAPE and LCA-MA indices for gold are expected to increase more with large-scale implementation, while currently negative indices may approach zero or even shift to positive values.

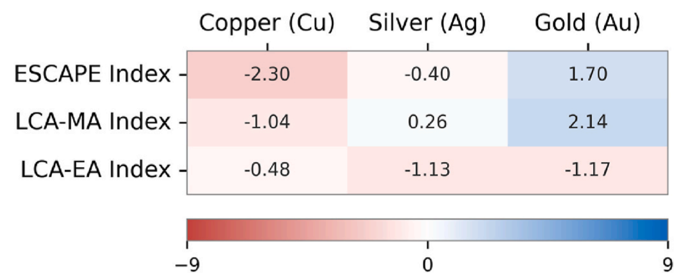

Fig. 7. Comparison between the ESCAPE and LCA-based indices calculated for copper, silver and gold. Blue cells (positive index) indicate that NMs recovery from e-waste is more environmentally advantageous compared to the primary extraction of the metal, while red cells (negative index) indicate that the extraction of the noble metal from natural resources results in a lower environmental load compared to the examined recovery method. The reported extremal values are derived from the ESCAPE index, generally ranging from −9 to +9 (Bontempi, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3.1. *Uncertainty analysis*

To assess the reliability of the LCA results, an uncertainty analysis was conducted using Monte Carlo (MC) simulation. The endpoint environmental score calculation was repeated 1000 times for both the recovery of 1 kg of copper, silver, and gold from waste RAMs and the primary extraction of these metals from natural resources. The ReCiPe 2016 Endpoint, H/A method was used for the calculations, taking into account the uncertainties of the LCI background datasets provided by the ecoinvent database.

Fig. 8 illustrates the probability distribution of the differences between the environmental scores of the primary metal and the recovered metal (ES_{PM} – ES_{RM}). Red columns indicate that metal recovery is environmentally less advantageous than the primary extraction, while blue columns show that recovery results in a lower environmental load compared to primary extraction. Detailed results of the MC simulation are presented in Table S30, including mean, median, standard deviation (SD), standard error of the mean (SEM), 2.5th percentile, 97.5th percentile and interquartile range (IQR). MC results indicate that, under mass allocation, copper recovery leads to higher environmental impact in 89.8 % of runs. In contrast, silver and gold recovery from waste RAMs exhibit a lower environmental impact compared to primary extraction in 84.7 % and 100 % of cases respectively. Under economic allocation, recovery is less environmentally favourable in 86.6 %, 89.4 %, and 91.0 % of runs for copper, silver, and gold, respectively. Considering a 95 % significance threshold, it can be concluded that the difference between

Table 8
Comparison between the ESCAPE and the proposed LCA indices, based on their definition, the environmental indicators used and their meaning.

	Definition	Environmental indicators	Meaning
ESCAPE index	$[\log[EE_{raw}/(MJ/kg)) - \log(EE_{sub}/(MJ/kg)) + \log(CF_{raw}) - \log(CF_{sub})]/2$	Carbon Footprint (CF) Embodied Energy (EE)	>0: the recovered metal (secondary - sub) is more advantageous than the raw material (primary - raw) from an environmental point of view <0: the raw metal (primary - raw) extracted from natural resources is more advantageous than the recovered one (secondary - sub) from an environmental point of view
LCA-MA index	$\log(ES_{primary}) - \log(ES_{recovered,\ MA})$	The Environmental Score (ES) is calculated using a damage-oriented LCIA method. It quantifies potential damages towards several areas of protection (i.e., human health, ecosystems, resources)	
LCA-EA index	$\log(ES_{primary}) - \log(ES_{recovered,\ EA})$		

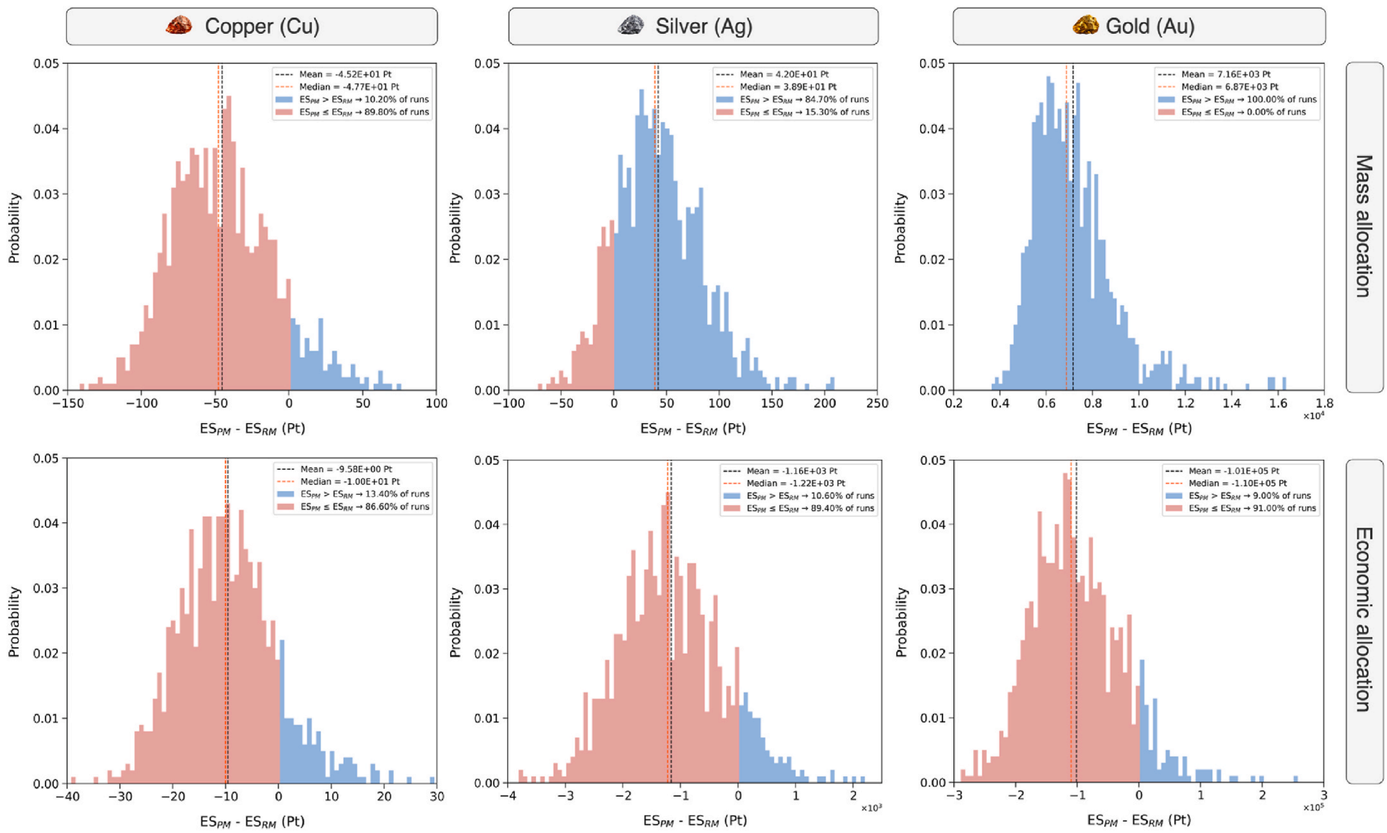

Fig. 8. Statistical distribution of differences in environmental single scores (Pt) associated with the extraction of 1 kg of Primary Metal (ES_{PM}) and the obtainment of 1 kg of Recovered Metal (ES_{RM}) from waste RAMs, based on a Monte Carlo simulation (1000 runs). Blue bars represent the probability of a positive difference, indicating that primary metal extraction results in higher environmental burdens compared to the assessed recovery method. Conversely, red bars indicate that the recovery method is less environmentally advantageous than primary extraction. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

primary and recovered metal is significant only for gold recovery under mass allocation.

The Monte Carlo simulations were performed considering only the uncertainties of the background datasets. However, variability in foreground parameters could also affect the results. As shown in Figs. 4 and 5, Leaching 1 and Leaching 2 contribute most significantly to the overall environmental score, primarily due to long leaching times and the associated use of laboratory equipment.

Under mass allocation, variations in the key input parameters of Leaching 1 and 2 could be effective in either increase or decrease the environmental score of all metals, given the relationship between recovered masses and partitioning factors.

The most uncertain foreground parameters concern energy consumption during the experimental procedures, which was often estimated from nominal power ratings and theoretical operating conditions (see e.g., Table S28), resulting in many cases in an overestimation of energy use. Improved primary data would reduce these uncertainties.

Other experimental parameters, such as leaching time, directly influence the environmental scores through their effect on energy consumption, while increases in recovery yields can positively impact the results, assuming other experimental conditions remain constant. Due to the non-linearity of the LCA-based index, changes in environmental scores do not translate linearly into index changes. For instance, reducing Leaching 1 from 48 h to 24 h decreases the mass-allocation environmental score by 18.5 %, but for silver, this corresponds to a 34.7 % increase in the index value. In the case of silver, to obtain a near-zero mass-allocation index (e.g., 0.05), the environmental score of the recovered metal would need to increase by approximately 60.4 %.

For economic allocation, gold showed the greatest influence on the allocation ratios due to its market price being roughly two orders of magnitude higher than silver, which in turn is about two orders of magnitude higher than that of copper. The economic allocation indices are therefore primarily influenced by the relative price ratios among the metals. Consequently, as long as these relative relationships remain stable (Au > Ag > Cu), absolute fluctuations in market prices are unlikely to significantly affect the indices, with gold consistently maintaining the highest partitioning factor.

3.4. An ESCAPE-LCA framework towards design for sustainability

The results of this study indicate that the ESCAPE index can be considered a valuable tool for identifying and contextualising environmental hotspots in a recycling system, revealing trends consistent with those obtained through Life Cycle Assessment. By translating primary energy and material contributions into carbon footprint and embodied energy metrics, the index effectively highlights a significant share of the system's potential environmental impact. This approach proves especially beneficial during early-stage experimental processes, where iterative assessments are needed to identify the most energy- and material-efficient configurations.

The proposed ESCAPE-LCA framework, presented in Fig. 9 for the recovery of NMs from waste RAMs, can be extended to similar recycling systems. By relying on indicators such as carbon footprint and embodied energy, a preliminary screening of the environmental profile of the analysed process can be quickly achieved, facilitating the identification of key areas for improvement. At this stage, major process modifications and integrations can be implemented to minimise environmental loads and guide the system towards more sustainable configurations.

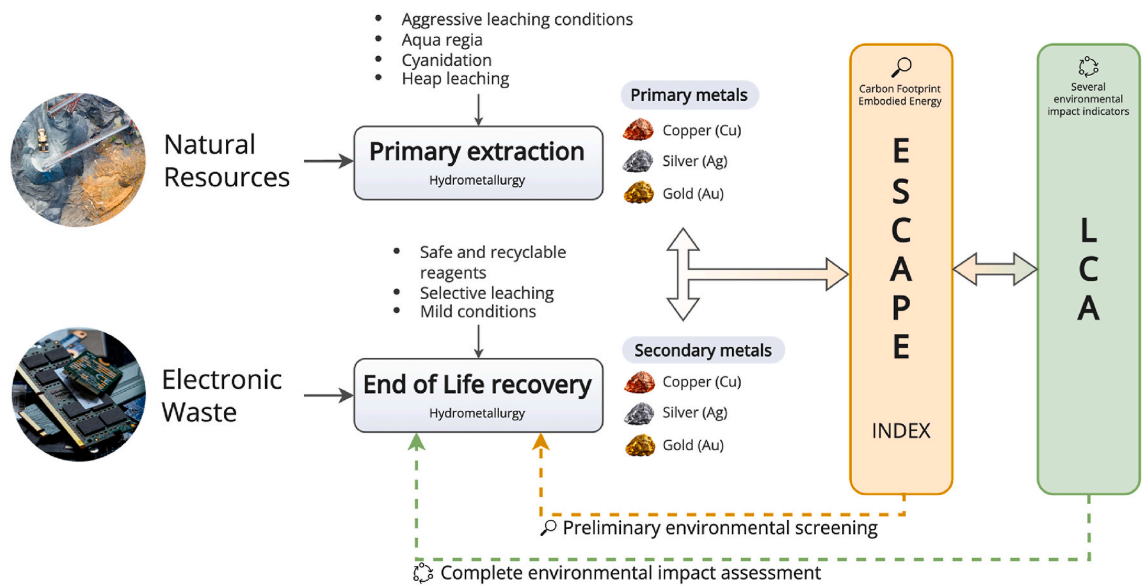

Fig. 9. The proposed ESCAPE-LCA framework. The ESCAPE index quickly provides a preliminary environmental assessment of the experimental method (i.e., noble metals recovery from e-waste), based on a few key indicators such as the Embodied Energy and the Carbon Footprint. A full LCA offers a comprehensive and more detailed evaluation of the potential environmental impacts, enabling further improvements in the sustainability of the secondary or recycled material being analysed (i.e., copper, silver and gold). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The subsequent application of LCA methodology to the refined system provides a more comprehensive evaluation of its overall environmental impact. This broader analysis can include extensive input datasets, advanced LCIA methodologies, and additional environmental impact indicators. Such an approach allows for the validation of the ESCAPE index results, along with the implementation of further sensitivity analyses, and the identification of potential trade-offs across environmental impact categories or life-cycle stages. Moreover, the framework's iterative closed-loop structure ensures that each modification to the experimental design can be re-evaluated using either the simplified ESCAPE index or a full LCA.

An operative platform for the validation of this model is the mentioned SMaRT PCBs project where the remarks and suggestions coming from the described preliminary ESCAPE-LCA assessment are being implemented in a version 2.0 of the noble metals recovery method from WPCBs. Specifically, the ongoing activity is facing the main issues raised by this work, focusing on the use of lactic acid by-derived from dairy waste as Leaching 1 dissolution agent in place of commercial citric acid, as well as on limiting heating stages and wastes as much as possible.

4. Sensitivity analyses

4.1. Consequential modelling

As described in the Section 2.3, the LCA modelling followed an attributional approach based on the APOS system model. To provide an alternative perspective on the results, a first sensitivity analysis was performed using the consequential modelling approach (system expansion or avoided burden). For this purpose, all background datasets from the ecoinvent database used in the LCI model were switched to the consequential system model. In this approach, multifunctionality is addressed through substitution instead of allocation (Wernet et al., 2016); therefore, all processes in which allocation was originally applied (e.g., recycling processes) were modified accordingly to ensure consistency with the consequential modelling logic.

In the foreground system, the treatment of waste RAMs enables the recovery of Cu, Ag, and Au, which were assumed to substitute the production of their respective primary metals. Consequently, the recovered

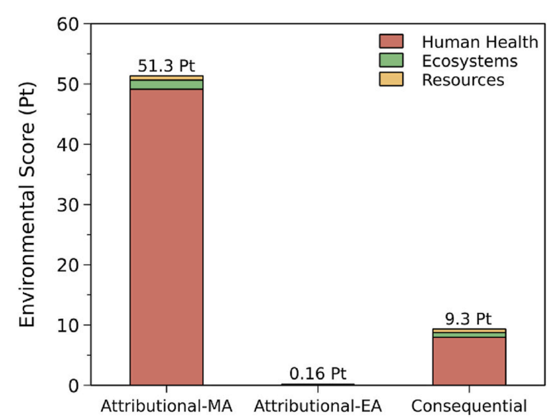

Fig. 10. Single score results (ReCiPe, 2016 Endpoint, H/A) associated with the treatment of 1 kg of waste RAMs for NMs recovery, comparing the attributional approach with mass (MA) and economic (EA) allocation to the consequential modelling approach.

metals were not treated as separate co-products, and the system expansion results couldn't be directly compared with the attributional mass- and economic-based results used for the comparison with the ESCAPE indices. The comparison was instead performed considering the treatment of a defined amount of waste RAMs (i.e., 1 kg). A detailed life cycle inventory of the NMs recovery process following the consequential system model is available in the supplementary data repository (Zenodo).

Endpoint results for the treatment of 1 kg of waste RAMs obtained using the three modelling approaches, i.e., attributional with mass allocation, attributional with economic allocation, and consequential, are presented in Fig. 10. The single score result from the consequential approach (9.3 Pt) is positioned between those from the attributional approach with mass allocation (51.3 Pt) and economic allocation (0.16 Pt). Fig. S3 in the supplementary data provides a breakdown of the relative contributions to the overall single score result for the consequential approach. The highest contribution arises also in this case from the Leaching 1 step (15.7 Pt), followed by Leaching 2 (4.39 Pt). Negative contributions (i.e., avoided environmental burdens) are primarily associated with the copper recovery step (−6.92 Pt), mainly due to the process "Spent solvent mixture {Europe without Switzerland}| treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | Conseq, U" which accounts for the incineration of the spent solvent mixture with energy recovery, providing a significant avoided burden for electricity and heat production. Significant negative contributions are also observed for the primary extraction of gold (−3.78 Pt).

4.2. Alternative attributional modelling

A second sensitivity analysis was conducted by adopting an alternative approach for the attributional LCA modelling. In this case, the environmental burdens were allocated, either by mass or economic value, exclusively among the valuable co-products obtained at the end of the treatment, without including the system's function. Each metal was directly assigned the process contributions required for its recovery. Accordingly, all three metals (Cu, Ag, and Au) were attributed a share of the impacts associated with RAMs milling, Leaching 1, and Leaching 2. For copper, the additional burdens related to its specific recovery process were also included. Contributions from Leaching 3 were divided between silver and gold, while those from Leaching 4 were entirely attributed to gold. Silver and gold were subsequently assigned the burdens associated with their respective recovery steps (i.e., Ag Recovery and Au Recovery). A visual representation of the process partitioning is shown in the flowchart in Fig. S4, while a detailed description of the LCI modelling approach adopted for this sensitivity analysis is provided in the supplementary data repository (Zenodo).

Endpoint single score results associated with the recovery of 1 kg of copper, silver, and gold under this modelling approach are reported in Table S31, together with the corresponding values for the primary extraction of the same metals, as previously shown in Table 7. These values were used to derive the mass and economic allocation-based LCA indices following Equations 3-4. The resulting LCA-MA and LCA-EA indices are presented in Fig. 11 for both the original attributional approach adopted in this study (coded M1) and the alternative attributional approach applied in this sensitivity analysis (coded M2), along with the ESCAPE index results (previously shown in Fig. 7).

Under mass allocation, clear differences emerge between the two approaches. These can mainly be attributed to the distinct modelling assumptions: in M1, the system's function was assigned the largest partitioning fraction (i.e., 90.4 %), whereas in M2, the burdens were

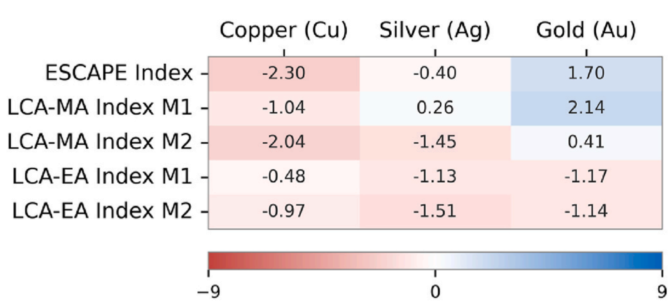

Fig. 11. Comparison between the ESCAPE and LCA-based indices calculated for copper, silver and gold, using two different attributional modelling approaches: M1 (default) and M2 (sensitivity analysis). Blue cells (positive index) indicate that NMs recovery from e-waste is more environmentally advantageous compared to the primary extraction of the metal, while red cells (negative index) indicate that the extraction of the noble metal from natural resources results in a lower environmental load compared to the examined recovery method. The reported extremal values are derived from the ESCAPE index, generally ranging from −9 to +9 (Bontempi, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

entirely distributed among the valuable co-products obtained at the end of treatment. This latter approach is more consistent with the one adopted for the ESCAPE index, in which environmental contributions (EE and CF) are allocated exclusively between each metal according to their initial content and recovery yield, effectively corresponding to a mass-based attributional approach. M2 results are negative for copper and silver and positive for gold, consistent with the ESCAPE outcomes, although with some differences in the absolute values, particularly for silver and gold.

For economic allocation, the two attributional approaches showed comparable results, negative for all metals. This can be attributed to the strong influence of gold's market price on the overall allocation, which drives a substantial portion of the environmental burdens towards gold. This trend is also evident in the M1 approach, where the system's function was assigned a small partitioning factor, thus minimally affecting the comparison between M1 and M2 approaches.

5. Limitations of the study

The following limitations should be considered when interpreting the results of this study:

- Both ESCAPE and LCA were applied to an early-stage, laboratory-scale method for the valorisation of a waste stream containing all metals combined. In contrast, the data related to primary extraction refer to well-established industrial-scale processes specifically optimised for the recovery of each individual metal. As a result, the outcomes associated with secondary metals may be overestimated and subject to greater uncertainty compared to a future upscaled process, optimised for the treatment of larger quantities of e-waste at an industrial scale.
- The two assessments focused exclusively on the environmental aspects, with ESCAPE limited to two indicators (carbon footprint and embodied energy) and LCA including 18 impact categories from the ReCiPe 2016 method. This limited the identification of other potential impacts or critical aspects related to the social dimension, such as issues associated with primary metal extraction in low-income countries, or the economic dimension, which has already been identified as an influent factor affecting both the market value of recovered metals and the economic feasibility of the waste treatment process itself.
- This study represents the first attempt to compare LCA with the simplified ESCAPE approach. The results presented here should therefore be validated by future studies comparing these two methods in different contexts and levels of technological development.

6. Conclusions and final remarks

In this work, the ESCAPE sustainability screening tool (Evaluation of Sustainability of material substitution using CArbon footPrint by a simplifiEd approach), based on embodied energy and carbon footprint metrics, was extensively analysed and validated in comparison with the Life Cycle Assessment (LCA) methodology. The comparative assessment focused on an innovative lab-scale hydrometallurgical method for recovering copper, silver, and gold from waste RAMs, utilising benign, selective, and recyclable reagents under mild conditions.

The ESCAPE index was calculated to evaluate the sustainability of the recovered noble metals relative to their primary extraction and reclamation from natural ores. The LCA provided a comprehensive understanding of the environmental performance of the recovery method, offering detailed insights across multiple environmental impact categories. This was achieved by applying both mass and economic allocation approaches, to address the multifunctional nature of the system under study, while also considering the quality and economic value of the recovered materials.

Despite the differing scales and levels of engineering of the processes considered, as well as the varying implications of working with virgin mining materials versus largely available scraps that would otherwise constitute hazardous waste for disposal, crucial deductions can be drawn regarding a potential iterative tool and its application for improving the sustainability of a future recovery process.

Both the ESCAPE and LCA analyses identified the first and second leaching steps as the primary environmental hotspots. This is largely attributed to the direct consumption of commercial citric acid and iodine during these treatments. Additionally, the LCA results highlighted a significant environmental burden from electricity consumption during the first leaching step, as well as the continuous operation of laboratory equipment, particularly during the second leaching step.

Damage-oriented LCA results were used to develop a logarithmic indicator, comparing the environmental load of primary metal extraction with that of recovered metals. Under mass allocation, the LCA-based indices aligned with the ESCAPE results for copper (negative values) and gold (positive values). However, in contrast to the negative ESCAPE index for silver, mass allocation-based LCA resulted in a slightly positive value, suggesting that the proposed recovery method is more environmentally favourable than primary extraction, despite the value being close to zero.

When applying economic allocation, the environmental burdens of silver and gold recovery exceeded those of primary extraction, emphasising the significant influence of allocation choices on the overall sustainability assessment. In this scenario, the LCA indices remained consistent with the ESCAPE results for copper and silver.

Furthermore, a Monte Carlo uncertainty analysis was performed to evaluate the robustness of the LCA results. At a 95 % confidence level, statistical significance was observed only for gold under mass allocation. In all other cases, the differences exhibited a significance level greater than 80 %. Moreover, two sensitivity analyses with different modelling approaches (i.e., consequential and alternative attributional approach) were conducted to better understand the influence of the modelling approach on the obtained results.

Overall, despite relying on only a few environmental metrics, the ESCAPE approach effectively pointed out a considerable portion of the system's potential environmental impacts, a conclusion supported by the LCA results.

Implementing a hybrid ESCAPE and LCA framework could be particularly advantageous for early-stage experimental processes, promoting the adoption of sustainable practices during the development phase. Future work should involve applying both simplified sustainability metrics and LCA to the same systems across a broader range of cases and scenarios. Further investigations are also necessary to explore critical aspects identified in this study, such as the influence of allocation methods on environmental assessment outcomes for both ESCAPE and LCA and to extend the comparative approach also to pilot and industrial-scale systems.

CRediT authorship contribution statement

Alessandro Francini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Antonella Cornelio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Elza Bontempi:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Angela Serpe:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition. **Anna Maria Ferrari:** Writing – review & editing, Supervision, Resources. **Paolo Neri:** Writing – review & editing, Software. **Roberto Rosa:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Dedication

To Nicolò Favoriti for his birth.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Angela Serpe reports financial support was provided by Italian Ministry of Environment and Energy Security (MASE), Call RAEE 2020, CUP F57G20000050001. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147016.

Data availability

The data and methodologies used to determine the ESCAPE and LCA indices – including calculations of embodied energy, carbon footprint, and complete life cycle inventories for the analysed processes – are openly available in Zenodo at https://doi.org/10.5281/zenodo.17348137, reference number 17348137.

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