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Evaluation of the environmental impact of direct hot rolling, ECAP and FSE for aluminum chips recycling

Mauro CARTA[1,a *], Pasquale BUONADONNA[1,b], Rayane El MOHTADI[1,c], Daniele LAI[1,d], and Mohamad EL MEHTEDI[1,e]

[1]Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo, 2, 09123 Cagliari, Italy

[a]mauro.carta94@unica.it, [b]buonadon@unica.it, [c]rayane.elmohtadi@unica.it, [d]daniele.lai@unica.it, [e]m.elmehtedi@unica.it

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Abstract. With the increasing global demand for aluminum, the environmental challenges associated with primary aluminum production, such as high energy consumption and greenhouse gas emissions, need innovative recycling solutions. Recently, unconventional aluminum recycling methods, known as Solid-State Recycling (SSR), have been developed. These processes bypass the melting stage, resulting in significant energy savings and reduced material losses. This paper presents a Life Cycle Assessment (LCA) study of the newly developed Direct Hot Rolling (DHR) process for recycling aluminum chips, focusing on the environmental impacts of chips degreasing and comparing DHR with other SSR methods. The DHR process, an emerging solid-state recycling (SSR) technology, offers a promising alternative to conventional methods by reducing energy use and emissions. However, the introduction of a degreasing phase is necessary to possibly scale the process for industrial applications, adding new environmental considerations. Using the SimaPro software with a "gate to gate" approach, this study evaluates the environmental performance of DHR both with and without the degreasing phase, to understand the environmental impact of this step. Then, based on data available in literature, the direct rolling process is compared with ECAP and FSE techniques. The results show that the degreasing process significantly contributes to aquatic and terrestrial ecotoxicity due to the chemicals used, highlighting a trade-off between material quality and environmental liability. On the other hand, DHR has a lower overall environmental impact if compared to ECAP and FSE. Additionally, DHR demonstrates significantly lower material losses compared to ECAP and FSE, making it more resource efficient.

Introduction

Aluminum is a key material in modern industries due to its exceptional properties, including lightweight strength, corrosion resistance, and recyclability [1]. It plays a fundamental role in sectors such as transportation, construction, packaging, and aerospace. However, the production of primary aluminum is a highly resource-intensive process [2]. Extracting aluminum from bauxite ore involves energy-intensive steps such as the Bayer process and electrolysis, leading to high greenhouse gas emissions and significant energy demands, with global aluminum production contributing substantially to industrial carbon footprints [3]. To mitigate these environmental impacts, recycling aluminum has become a critical focus challenge. Recycling aluminum requires only about 5% of the energy used for primary production, making it an attractive option for reducing both emissions and cost [4].

Despite the benefits of recycling, traditional methods, which often involve melting aluminum scrap, are not without their problems. Melting processes can result in energy losses and material degradation due to oxidation, reducing the overall efficiency and environmental benefits [5]. A comprehensive LCA analysis of traditional processes was performed by Astarita et al. [6]. To address these issues, innovative solid-state recycling (SSR) technologies have been developed. These methods, which bypass the melting stage, have the potential to minimize energy consumption and material losses, while improving the sustainability of the entire recycling process. SSR processes can utilize either plastic deformation or sintering techniques, including methods such as: Direct Extrusion [7,8], Equal Channel Angular Pressing (ECAP) [9], Friction Stir Extrusion (FSE)[10,11], Direct Hot Rolling (DHR) [12], and Spark Plasma Sintering [13]. A previous study from these authors, focus on the LCA analysis of DHR and DHR using Accumulative Roll Bonding process [14,15]. This paper, instead, focuses on evaluating the environmental impact of DHR, specifically considering the effect of chemical degreasing on the process. Additionally, three SSR techniques are compared: Direct Hot Rolling (DHR), Equal Channel Angular Pressing (ECAP), and Friction Stir Extrusion (FSE). Using a Life Cycle Assessment (LCA) approach, the analysis examines these techniques in terms of overall ecological impact.

Methodology

Goal and Scope definition. The objective of this analysis is to evaluate and quantify the environmental impact and emissions associated with the solid-state recycling (SSR) technique of direct hot rolling, including a chips cleaning phase.

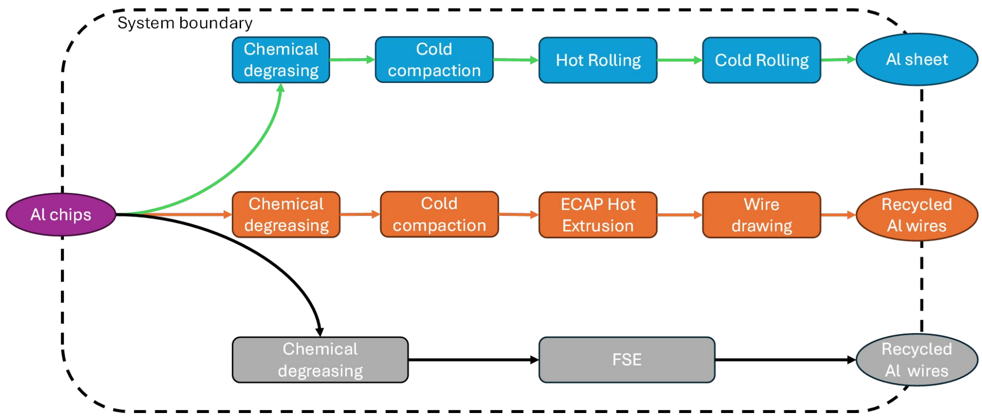

Figure 1 – System boundaries for the considered processes

The following LCA analysis on the DHR is based on the experimental results detailed in [16] obtained in the recycling of AA6063 chips, where a detailed analysis of mechanical properties and microstructural properties is presented. The life cycle assessment (LCA) of the direct hot rolling process was previously presented by Carta et al. [15]. However, this analysis introduces a preliminary chips cleaning phase upstream in the process, aimed at removing oil and lubricant residues, that is fundamental to scale the process to an industrial level. A comparison will subsequently be made between the two methods (with and without chips cleaning) to highlight the differences and environmental impacts of the newly introduced step.

The analysis was conducted using the SimaPro™ software, following a "gate-to-gate" approach, as the focus of the study is limited to the production process. The functional unit for this analysis is defined as a 31.5 g aluminum sheet produced from 35 g of chips through direct hot rolling, consistent with the analysis presented in the previously cited article. All input and output data are aligned with this functional unit**.** The process was divided into several unit operations (Fig. 1), corresponding to the stages of the process: chips cleaning, cold compaction, hot rolling, and cold rolling.

Life Cycle Inventory (LCI) Analysis. Energy consumption and material use for each process were quantified during this phase. Material and energy flows, both input and output, were defined for the various identified unit processes. The data used are consistent with those in [15], where the primary data were obtained from direct measurements provided by an industrial plant producing aluminum sheet and laboratory measurements. The secondary data were sourced from databases within the SimaPro software and various studies available in literature. In the initial phase, chips cleaning, the inputs consist of aluminum chips sourced from a turning process external to the system boundaries, along with the energy and materials required for the degreasing bath selected as the cleaning method. This step was modeled using the Ecoinvent database (Degreasing in alkaline bath), assuming a surface-to-volume ratio of 1m^2/kg as detailed in [17]. The output consists of clean aluminum chips. For the input dataset on the aluminum chips, the "Aluminum scrap, post-consumer {GLO}" dataset which is available in the software was utilized.

Table 1 – Inputs and Outputs of the DHR Process with Chips Cleaning

Chemical Degreasing			Cold Pressing			Hot Rolling			Cold Rolling		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Al chips	35	g	Cleaned chips	35	g	Compacted chips	35	g	HR sheet	31.5	g
Degreasing (Ecoinvent)	0.035	m^2	Electric energy (pressing)	0.0017	MJ	Electric energy (heating)	0.0631	MJ	Electric energy (rolling)	0.0091	MJ
						Electric energy (rolling)	0.0176	MJ			
						Water (cooling)	$4.732 \cdot 10^{-5}$	m^3			
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
Cleaned chips	35	g	Compacted chips	35	g	HR sheet	31.5	g	CR sheet	31.5	g
						Al scrap	3.5	g			

For the second process (cold pressing), the inputs include the cleaned chips from the previous phase, along with the energy required to operate the press. The calculation of electrical consumption utilized the dataset “Electricity, high voltage, IT, APOS,” with values consistent with those used in the previous step. The subsequent phase, hot rolling, involves the preheating and rolling of the compacted sample, which serves as the material input for this stage. Inputs for this phase include the electrical energy required for the rolling mill and the furnace for preheating. Additionally, water for cooling the rolls during the rolling process is also considered as an input. Outputs include the rolled aluminum sheet and a 10% material loss corresponding to jagged edges that need to be removed. The same dataset was used for energy consumption in this phase. Finally, cold rolling is performed in a single pass to reduce the sheet thickness from 1.5 mm to 1.0 mm, which represents the only output of this process. Inputs for this stage include the rolled sheet from the preceding phase and the electrical energy required for the rolling operation, calculated using the same dataset mentioned earlier.

Lyfe Cycle Impact Assessment (LCIA) and results. In this phase of the LCA, environmental impacts were analyzed using the SimaPro™ software. The evaluation was conducted employing the IMPACT 2002+ v2.15 method. The previously described unit processes were modeled within the software, enabling a comparison to understand the environmental impact of each phase in the direct hot rolling process. Using these unit processes, two distinct life cycle scenarios were created within the software: one for direct hot rolling with chips cleaning and another without chips degreasing.

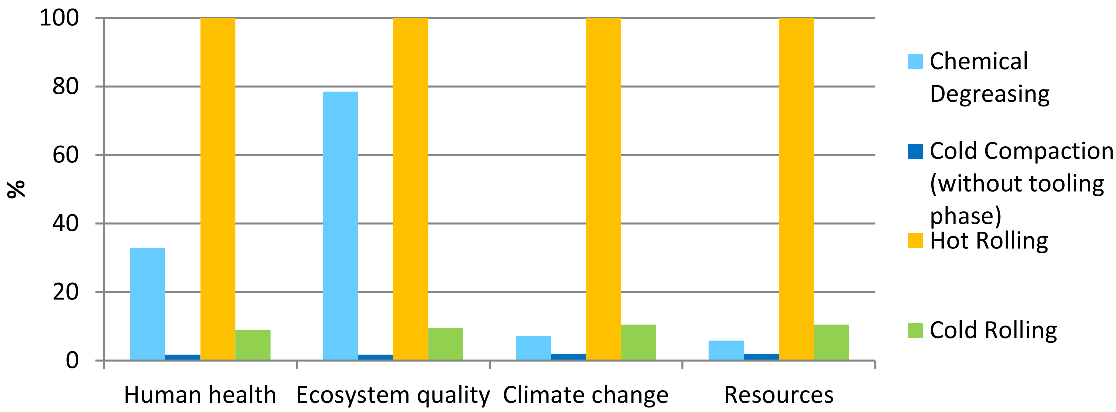

Figure 2 – Damage categories analysis of Direct Hot Rolling with chips degreasing

Fig. 2 illustrates the environmental damage caused by the Direct Hot Rolling (DHR) process with the inclusion of a chips cleaning phase. Chemical degreasing emerges as a higher contributor to human health and ecosystem quality. This is primarily due to the use of chemicals and energy in the cleaning process, which significantly impacts both ecosystem quality and human health. The hot rolling phase shows the highest contributions to all categories.

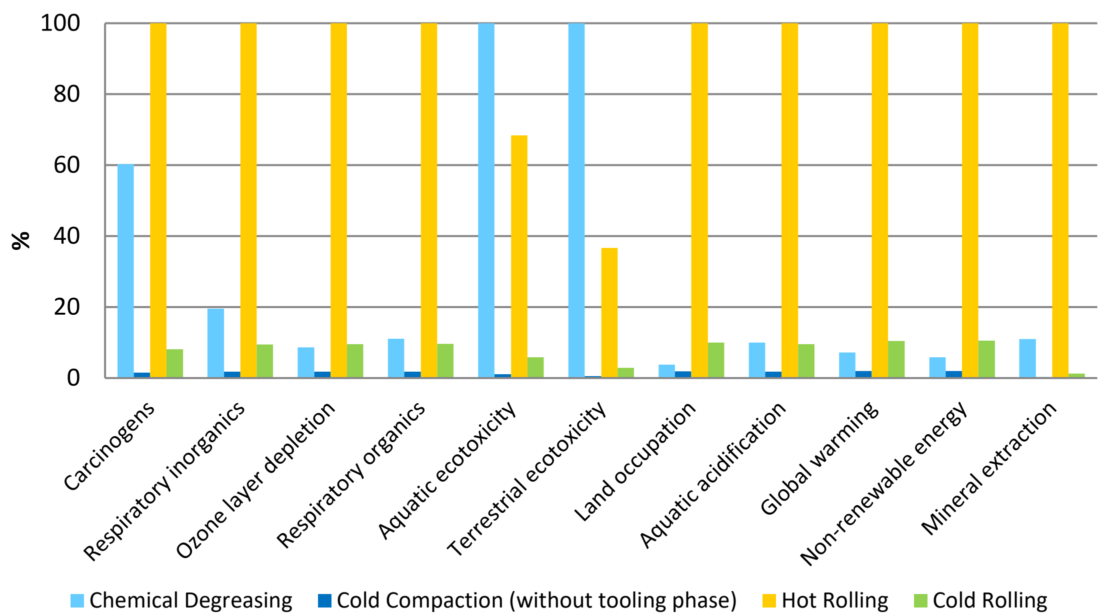

Figure 3 – Impact categories of the four units of DHR process

This is due to the high energy consumption required for the heating and rolling processes. Cold rolling and compaction contribute relatively less to the overall environmental impact if compared to chemical degreasing and hot rolling. Fig. 3 provides an insightful breakdown of the environmental impact categories associated with the Direct Hot Rolling (DHR) process. The graph highlights that chemical degreasing has the highest contribution to environmental impact categories such as aquatic and terrestrial toxicity and a very high contribution in carcinogens. This is due to the chemicals used in the cleaning process, which introduce pollutants into ecosystems. While the hot rolling phase also has the highest contribution in all the other categories, because of its high energy requirements. Cold rolling and compaction have relatively smaller impacts, primarily limited to energy consumption.

Fig. 4 shows the results obtained through the single-score analysis. The single-score indicator summarizes the environmental impacts of the process by combining the results from the four impact categories (resources, human health, climate change, and ecosystem quality) into a single value, providing a comprehensive view of the environmental aspects.

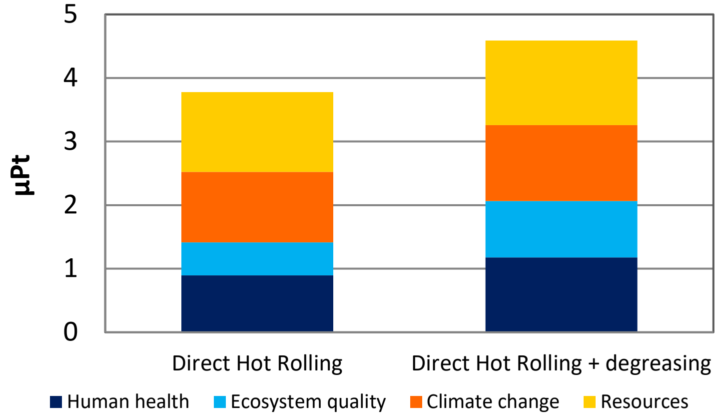

Figure 4 – Results comparison of DHR with and without chips cleaning (single score analysis)

The bar chart illustrates a comparison between the environmental impacts of Direct Hot Rolling (DHR) and Direct Hot Rolling with Degreasing (DHR + Degreasing), measured in µPt across categories such as human health, ecosystem quality, climate change, and resource depletion. The total impact for DHR is 3.8 µPt, while DHR + Degreasing increases to 4.6 µPt, representing a 21.5% rise in overall environmental impact. This increase is due to the degreasing phase, which adds significant environmental burdens, particularly in the ecosystem quality and human health damage categories. Although the degreasing phase enhances the quality of the recycled aluminum by reducing contaminants and improving product properties, it comes at the cost of increased environmental impact. The 21.5% rise underscores the trade-off between achieving higher material quality and maintaining sustainability.

LCA Analysis: Comparison of DHR, ECAP, and FSE

This section presents the LCA analysis comparing three innovative solid-state aluminum recycling techniques, discussed in more detail in the first chapter: direct hot rolling (DHR), friction stir extrusion (FSE), and equal channel angular pressing (ECAP).

Goal and scope definition. The objective of the comparative analysis among the three processes listed above is to provide a clear understanding of the environmental impacts associated with each process, aiming to identify the one with the least impact. For this analysis, the SimaPro software was used, employing a "gate-to-gate" approach. The functional unit for the comparative analysis is defined as the production of 1 kg of aluminum in the final form of either sheets (for DHR) or extruded wire (for ECAP and FSE). This definition ensures an equitable basis for comparison of the environmental impacts across different SSR technologies, since there are no other SSR processes that exclusively produce sheets, with the exception of DHR.

Life Cycle Inventory (LCI). Each technique selected for the analysis was broken down into several unit processes. For all three processes considered, the starting point was a preliminary cleaning phase for the material to be recycled, using the same type of aluminum chips and a cleaning treatment involving an alkaline bath. For this initial phase, the calculation of material and energy requirements referenced the work of Duflou et al. [17] and the Ecoinvent dataset. The unit processes comprising the direct hot rolling process with the addition of cleaning are the same as those identified in the previous analysis: chips cleaning, cold compaction, hot rolling, and cold rolling (Fig. 1). Input and output flows for each process were recalculated, compared to the previous case, to provide 1 kg of final product as the output. Since the material loss is 10%, the aluminum required at the process input to produce 1 kg of aluminum sheet is 1.1 kg. For the energy requirements of the process, they are calculated proportionally. The Input and Outputs are presented in Table 2.

Table 2 – Inputs and outputs of the DHR process with chips degreasing

Chemical Degreasing			Cold Pressing			Hot Rolling			Cold Rolling		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Al chips	1.1	kg	Cleaned chips	1.1	kg	Compacted chips	1.1	kg	HR sheet	1	kg
Degreasing (Ecoinvent)	1.1	m^2	Electric energy (pressing)	3.29	MJ	Electric energy (heating)	1.98	MJ	Electric energy (rolling)	0.29	MJ
						Electric energy (rolling)	0.55	MJ			
						Water (cooling)	1.49	dm^3			
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
Cleaned chips	1.1	kg	Compacted chips	1.1	kg	HR sheet	1	kg	CR sheet	1	kg
						Al scrap	0.1	kg			

The ECAP and FSE processes were divided into unit processes (Fig. 1) based on the analysis conducted by G. Ingarao et al. [10]. This study also provided data related to primary energy flows. Subsequently, the primary energy used by these two processes was converted into electrical energy consumption, assuming a 34% efficiency, in accordance with the same study. In the following, the input and output flows for each unit process within the ECAP system are analyzed, with corresponding tables provided to present the values used (Table 3). For the cleaning process, the inputs include chips obtained from milling, an operation external to the system boundaries, and the Ecoinvent dataset, which accounts for the materials and energy required for the degreasing process in accordance with Duflou et al. [17]. At the end of this process, the output consists of cleaned chips, ready for subsequent processing.

In the next phase, hot compaction, the cleaned chips serve as the input flow for the process. During this stage, the chips are transformed into a compacted specimen using a press. The energy required for the press constitutes an additional input flow for the process. The dataset used to reference energy consumption is "Electricity, high voltage, IT, APOS S," with the same value as that used in the study by G. Ingarao et al. [10]. In the third unit process, hot extrusion, the previously compacted specimen is extruded through an angular channel die. This phase requires not only the compacted specimen as input but also the energy needed for the extrusion process. The outputs of this operation include extruded products and a certain amount of material waste. Finally, the wire drawing process is employed to produce 1 kg of aluminum wire. This phase takes the extruded product from the hot extrusion stage as input, along with the energy required for the drawing operation.

Table 3 – Inputs and outputs for the ECAP process

Chemical degreasing			Cold compaction			ECAP hot extrusion			Wire drawing		
INPUTS	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**	**INPUTS**	**Quantity**	**Unit**
Al chips	1.48	kg	Cleaned chips	1.48	kg	Compacted chips	1.48	kg	Hot extruded chips	1.11	kg
Degreasing	1.48	m^2	Electric energy	4.42	MJ	Electric energy	6.44	MJ	Electric energy	6.42	MJ
OUTPUTS	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**	**OUTPUTS**	**Quantity**	**Unit**
Cleaned chips	1.48	kg	Compacted chips	1.48	kg	Hot extruded chips	1.11	kg	Al wires	1	kg
						Al scrap	0.37	kg	Al scrap	0.11	kg

For the FSE process study, as already mentioned, the assumptions and data provided in [10] were adopted. Fig. 1 presents a schematic of the process, outlining the system boundaries for the analysis. For the FSE process, as with the previous processes, a preliminary cleaning phase of the chips is included before extrusion. This cleaning phase uses the same calculation employed for direct hot rolling and ECAP. Thus, the input flows for this initial phase consist of aluminum chips. Again, the Ecoinvent dataset for chemical degreasing is used, which includes information on energy consumption and materials required for alkaline baths. In the subsequent extrusion phase, the inputs include cleaned chips, and the energy required to produce 1 kg of aluminum wire. This energy value was experimentally determined by G. Ingarao et al. [10]. At the end of the process, the outputs consist of extruded wire and material waste amounting to 0.324 kg.

Table 4 – Inputs and outputs for the FSE process

Chemical degreasing			FSE		
INPUT	**Quantity**	**Unit**	**INPUT**	**Quantity**	**Unit**
Al chips	1.324	kg	Cleaned chips	1.324	kg
Degreasing	1.324	m^2	Electric energy	10.59	MJ
OUTPUT	**Quantity**	**Unit**	**OUTPUT**	**Quantity**	**Unit**
Cleaned chips	1.324	kg	Al wires	1	kg
			Al scrap	0.324	kg

Lyfe Cycle Impact Assessment (LCIA) and results. This section presents the environmental impact analysis conducted using specialized software and the IMPACT 2002+ v2.15 method for evaluation.

The previously described unit processes were used to construct specific life cycle models for each process within the software. A comparison was then carried out among the created life cycles. The results of this comparison are shown in the graph in Fig. 5, which displays the single scores for the three processes.

The graph reveals that the solid-state recycling process with the highest environmental impact is ECAP, as it shows a higher μPt value compared to the others, followed by FSE. This result is likely due to the significantly higher energy consumption of the ECAP process, which also includes wire drawing, a highly energy-intensive stage.

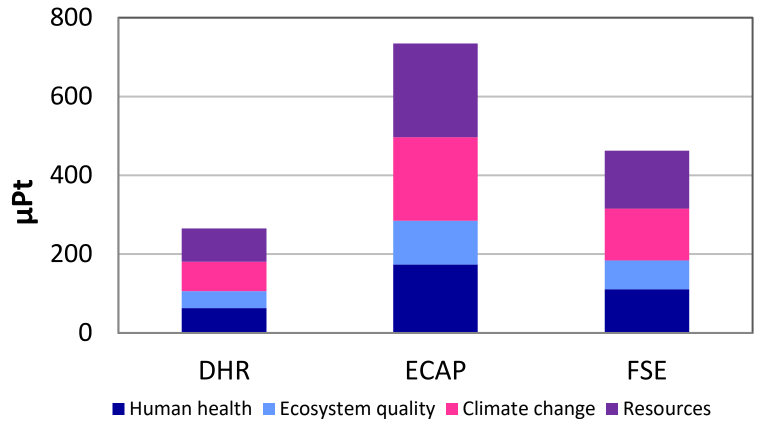

Figure 5 – Single score comparison of DHR, ECAP, and FSE

These results align with those shown by Ingarao et al. [10], as the ECAP technique involves more substantial plastic deformations, further contributing to its elevated energy demands. From this comparison, direct hot rolling emerges as the most sustainable aluminum recycling method among the three processes. The reason lies in the fact that rolling is a faster process than FSE and ECAP, making it significantly less energy intensive.

Fig. 6 presents the characterization results for the three processes across the eleven selected impact categories. This diagram provides a more detailed view of the environmental impacts, allowing for the identification of which categories contribute most significantly to the overall impact.

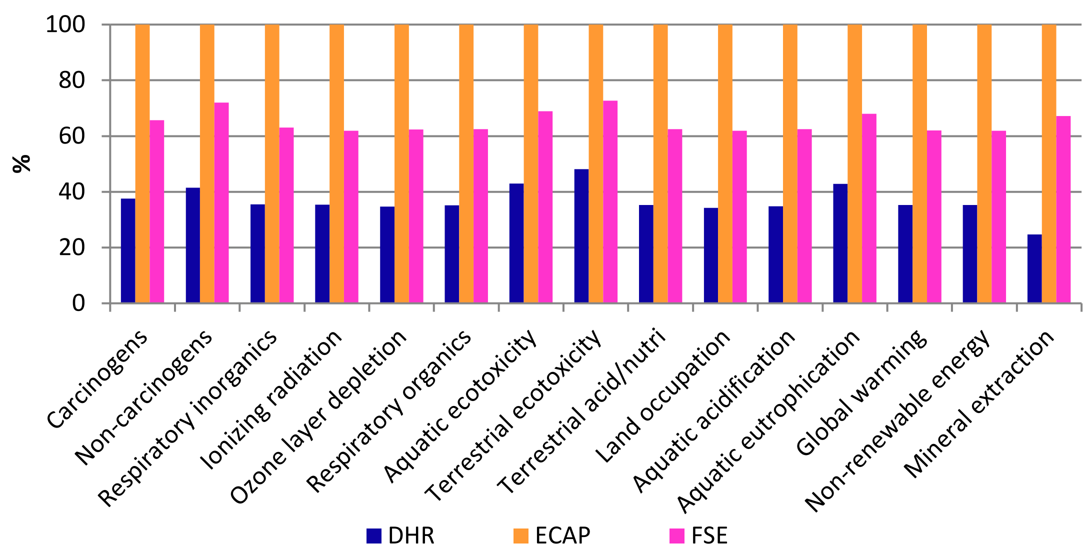

Figure 6 – Impact Categories results of the three processes (DHR, ECAP, and FSE)

Summary

This study presented a comprehensive evaluation of the environmental impacts associated with three innovative solid-state recycling (SSR) processes for aluminum chips. The results can be summarized as follows:

- The inclusion of a chips degreasing phase in the DHR process enhances the quality of recycled aluminum by effectively removing contaminants, making it a necessary step for the industrialization of the process. However, this improvement comes with an increased environmental burden due to higher resource and chemical usage. Despite this drawback, the trade-off can be justified by the production of higher-quality recycled materials, which ultimately reduces the long-term demand for primary aluminum, contributing to greater sustainability

- DHR emerges as the most environmentally sustainable method among the three processes. It demonstrated significantly lower energy consumption and material losses compared to ECAP and FSE
- FSE and ECAP, while effective in recycling, exhibited higher environmental impacts primarily due to their greater energy demands if compared to DHR that is a faster process. Despite their higher impacts, these methods may be preferred in applications requiring specific mechanical properties or product forms not achievable through DHR

Future research should focus on optimizing the chips cleaning phase and exploring hybrid approaches that combine the strengths of these SSR methods. This will further enhance the sustainability of aluminum recycling, contributing to a more circular economy in the aluminum industry.

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