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ALUMINUM RECYCLING, INNOVATIONS AND FUTURE PERSPECTIVES: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Aluminum has become a widely used metal, both for its availability and for its mechanical characteristics. However, its cost of transformation in the primary process is very high, especially in relation to the energy used. In this way, recycling processes are gaining ground with an environmental as well as an economic bias. The objective of this study was to evaluate the advances and innovative processes in relation to the recycling of aluminum, in particular, for the development of alloys that present conductivity; as well as identifying the main authors who have published on this topic in the last 5 years. A systematic literature review was carried out on three pre-selected databases (Scopus, Science Direct and WoS). From this literature review, 4,813 valid articles were found in 03 databases that mentioned the search terms: innovation, aluminum and recycling. These articles have been indexed and compiled. The progress of the four main authors with the most publications was analyzed and as a relevant result it was found that innovations in the area of aluminum recycling are not related to product innovation issues. The recycling processes are being treated as mere ways to obtain the raw material in the development of products.

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INTRODUCTION

In the 1970s Bruner *et al*. (1976) presented aluminum scrap and its possibility of recycling, where there were already signs of problems existing in secondary alloys due to various impurities generated from recycled aluminum. In 1979, the problems reported by domestic impurities in aluminum recycling processes were already being discussed in the Financial Times (Cartwright, 1979). In 1982 the connection between aluminum and Solar Photovoltaic Energy was already studied, mainly with the use of aluminum from the thermal processes that the studies involved (Van Overstraeten; Mertens; Nijs, 1982). However, a major disadvantage is that the production of primary aluminum consumes approximately nine times more energy than the production of primary steel (Zhu *et al*., 2021). In 1998, Andrade *et al*. (1998) conducted a study in Brazil evaluating the advantages of replacing steel with aluminum in beverage cans. Thus, aluminum has been considered a lighter and more viable alternative to steel for a long time. Aluminum recycling, driven by the production of secondary aluminum alloys, has grown in recent decades, mainly driven by energy savings of around 95%; this brings significant environmental and economic benefits over primary production (Kotadia *et al*., 2020). In this sense, recycling aluminum may reduce energy costs. According to Holzschuh *et al*. (2020), one of the differentials of aluminum, is the ability to recycle without losing its physical / chemical properties, which makes it an excellent metal, especially for beverage packaging. However, recycling aluminum packaging waste is difficult if we use traditional casting methods (Al Mahmood *et al*., 2020). The ability to recycle aluminum scrap in a closed circuit is determined by the quality (homogeneity of composition) of the scrap stream (Zhu *et al*., 2021); but with more and more composite materials being presented on the market, alternative systems may be presented as viable in this recycling process. Therefore, this article, through a systematic review of the literature, sought to assess the innovative advances in aluminum recycling for alloys with conductivity, as well as to identify the main authors who have published on this topic in the last 5 years. This analysis of the literature may bring subsidies for sustainable advances in aluminum recycling, therefore, a better energy assessment of this system and its possibilities for improvement.

In the section subsequent to this introduction, we find the methodology used that provided the methodological framework for this research work. Then, in the third section, the results are presented and discussed. The presentation of this article ends with the conclusions about the study carried out.

METHODOLOGY

Starting from the objective of this study, the following research questions were defined:

Q1 - What are the methods and / or tools used to promote improvements in the aluminum recycling process with a focus on the development of conductivity in aluminum alloys?
Q2 - Who are the main authors who have published on this topic in the last 5 years?

From these research questions, the search terms and the chain of command used were defined: "innovation" and "recycling" and "aluminum". The period of research in the databases was defined from 2016 to 2020. Only research articles and / or review articles were the documents evaluated, considering that these two classes group the largest number of articles in a very significant way. The bases of selected journals were: Scopus, Science Direct and Web of Science, as they are multidisciplinary and world-renowned databases. The collected documents were indexed by the Mendeley software (Mendeley, London, UK - Foeckler *et al*., 2019), as this software is free of charge and well regarded in the worldwide research community. About the Mendeley, the analysis of duplicity of the articles was made. The PRISMA protocol (Moher *et al*., 2010) was used for the development of this study. Table 1 shows a summary of the methodological procedures used in this study.

Table 1. PRISMA Protocol Adapted from (Moher *et al*., 2010)

Identification	✓ Database: The Scopus, Science Direct and Web of Science databases are recognized as the most important in the area of science and technology. ✓ Keywords: "innovation"; "recycling"; "aluminum". The key words were associated according to the following list: ✓ Search string: "innovation" and "recycling" and "aluminum". ✓ Years Publication / Language: The selection criteria were developed taking into account the period from 2016 to 2020. Language: only texts in English.
Screening	✓ Analyze duplicity: Mendeley software version 1.19.4 was used to support duplication between selected articles. ✓ For the authors' analysis, the following criterion was created: the authors were identified who presented at least 10 published documents.
Eligibility	✓ Select only articles published in journals present at JCR 2018 (Journal Citation Reports).
Inclusion	✓ Analysis of the summary of the other articles published in the last 5 years, and if there are relations with the research questions, carry out the inclusion.

Afterwards, the selected references were exported to the VOSVvewer software (Van Eck; Waltman, 2020).The results obtained in the VOSViewer software, both for the analysis of keywords and for the analysis of relevance of authors, are being presented in graphical form in the next section. Thus, it follows with the analysis of the theme with a focus on innovations in recycling aluminum for alloys that have conductivity and the relevance of the main authors.

RESULTS

The collection of data in the databases resulted in 4,816 articles divided as follows: 2,816 articles collected in Science Direct, 1,972 articles in Scopus and 28 articles in Web of Science. Of this total, 03 articles were published in duplicate, resulting in a valid total of 4,813 articles, among the criteria already established in the methodology. After exporting these references to the VOS Viewer software, it was noticed that for the keyword aluminum, there were some variations. In this way the variations: "aluminum alloy", "aluminum alloys", "aluminum" and "aluminum alloys", were manually set to "aluminum". This adjustment resulted in 9,266 keywords collected. As a form of restriction, it was stipulated that for a keyword to be considered significant, it must appear at least 12 times and thus the limit of 74 keywords was found. Still as a form of restriction, words that the software identified with a link strength less than or equal to 5 were eliminated. The strength of the link indicates the interconnection that the key word, or the author has with other keywords, or authors , or publications of the Van Eck and Waltman (2020). The list of 10 keywords with higher occurrence and link strength can be seen in Table 2 and the interpretations of these results can be seen in the discussions of each graph.

Table 2. Keywords after VOSviewer filtering

Index	Keyword	Ocorrunces	Link strenght
1	recycling	156	138
2	circular economy	130	146
3	life cycle assessment	116	110
4	sustainability	105	97
5	additive manufacturing	56	46
6	adsorption	56	24
7	china	44	29
8	mechanical properties	43	10
9	lca	42	47
10	waste management	41	35

The results of the analysis of these keywords, in view of their correlations and interconnections can be seen in Figure 01.

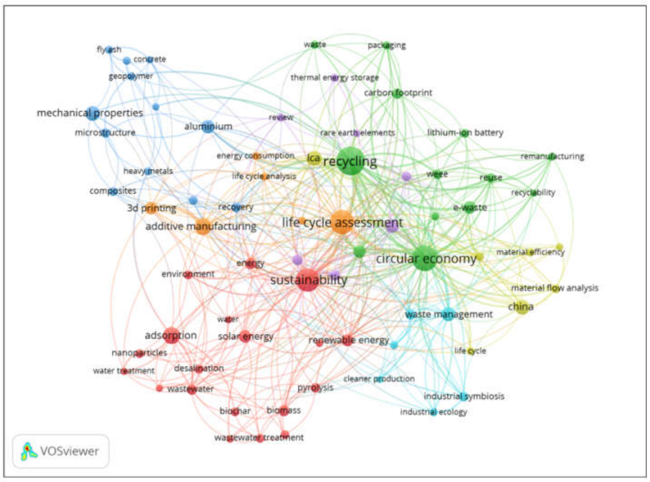

Fig. 1. Correlations between the keywords found

It is noted that the concepts of recycling, circular economy, sustainability and life cycle assessment are central and major concepts, and that interconnect practically all other concepts in smaller proportions. The large number of publications linking the search terms "innovation"; "recycling"; and "aluminum", occurred in 2018 and it is clear that from 2019, interest began to migrate to terms such as energy, waste and additive manufacturing. When looking to see the interconnection between the three groups of keywords more specific to this bibliometry, we have the following results:

- The concept of recycling is the strongest. It is interconnected with "aluminum", but it is not directly interconnected with innovation. Recycling is linked to life cycle assessment, circular economy, sustainability, additive manufacturing and several other related concepts.
- The concept of aluminum, remembering that this keyword has undergone the indexing of aluminum alloys, is strongly interconnected with recycling, life cycle assessment and circular economy, but goes beyond addressing aspects such

as microstructure, mechanical properties, geopolymers, packaging , water and the sustainability of manufacturing itself. Figure 02 illustrates these correlations. Figure 02 (a) and 02 (b) illustrates these relationships.

- The concept of innovation, in this research, is strongly linked to the sustainability part, both in development, in wastewater, water treatment and life cycle assessment. Note that this criterion was out of the main focus, containing only 12 appearances of the keyword (search minimum) and also a link strength equal to 7.

With all the keywords correlated and with their main groupings indicated, we proceeded to the authors' evaluation. With the same criteria used for the keywords, a total of 18,028 authors were obtained, present in the set of 4,813 indexed articles. For a more in-depth analysis, a screening of authors was carried out, as indicated in the section on the methodology. 60 authors were found with at least 10 documents published. From this number, those with link strength less than or equal to 05 and stray authors who did not interconnect with the main nucleus were excluded. Thus, the total number dropped to 54 valid authors.

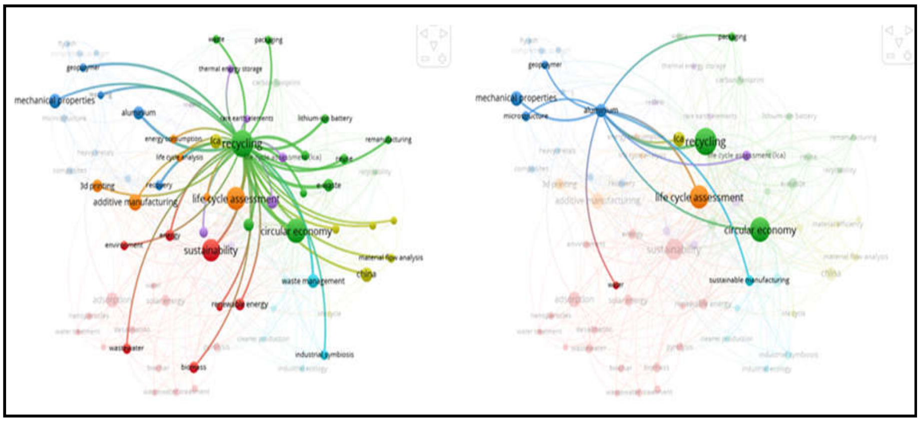

Figure 2. Recycling and its direct interconnections (a = left), and Aluminum and its direct interconnections (b = right)

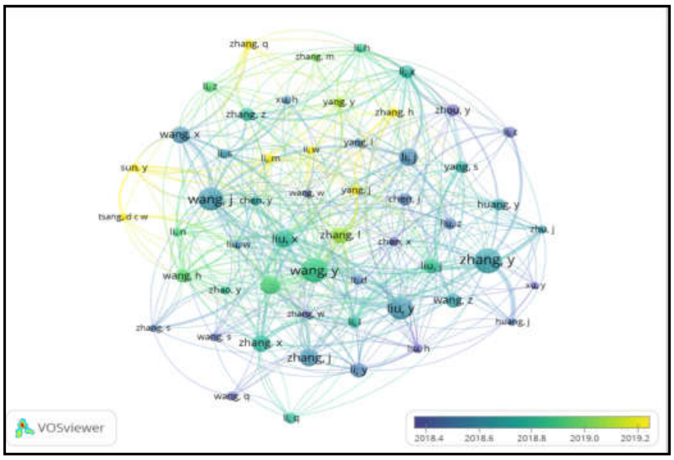

Figure 3. Correlation of the 54 selected authors

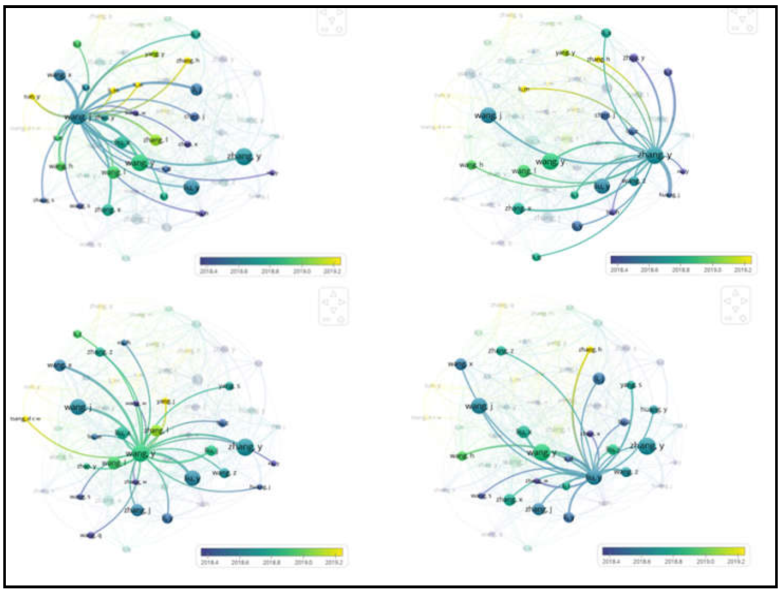

Figure 4. (a = up left) Correlation of authors from Wang, J., (b = up right) correlation of authors from Zhang, Y., (c = down left) correlation of authors from Wang, Y. and (d = down right) Correlation of authors from Liu, Y

Of this group of authors, the following stand out: Zhang, Y. with 32 articles; Wang, Y. with 31 articles and a total of 38 links between authors; Wang, J. with 29 articles and 45 links between authors; and Liu, Y. with 28 articles. Figure 03 illustrates the correlation of the 54 authors. The chronological line on a colorimetric scale is not significant, as it varies by one year. On the other hand, it can be seen that from the analysis of Figure 4 (a) (b) (c) e (d) that the author Wang, J. has the best correlations, because in addition to being interconnected with all or other authors, he is also interconnected with the authors who made the latest publications.

ANALYSE

Knowing that Wang, J.'s articles could contain the most relevant data according to the stipulated criteria, we proceeded to analyze the 29 documents published by this author. This analysis reached the following result: only one article entitled “Environmental friendly technology for aluminum electrolytic capacitors recycling from waste printed circuit boards”(Wang; Xu, 2017), proved to be compatible with the focus of this research. The other 28 articles by the author dealt with topics related to wastewater treatment, recycling processes not correlated with aluminum and processes for energy sources. In response to the study proposed by Wang and Xu, after crushing and screening, a recovery of 96.52% of aluminum and 98.68% of iron was achieved. The purity indices were 99.03% for aluminum and 98.24% for iron (Wang; Xu, 2017). When Zhang, Y.'s articles were analyzed, it was noticed that many dealt with lithium compounds and battery recovery. Some on microstructures of sintered alloys; others permeate recycling and leaching, but only one article focused on aluminum alloys. The article “Feasibility study of dissimilar joining of aluminum alloy 5052 to pure copper via thermo-compensated resistance spot welding” (Zhang *et al*., 2016).

In this research, the authors did not go against recycling processes, but proposed combined uses between copper and aluminum for a resistance spot welding process. As a result of the research, the welding of copper and aluminum tapes had a shear load capacity of the thermo-compensated resistance joints, comparable with the aluminum x aluminum spot welding joints (Zhang *et al*., 2016). In the analysis of Wang's articles, Y. it was noted that research was done on recycling, energy systems, batteries, waste heat treatment, performance of aluminum alloys, among other subjects. No article specifically focused on recycling aluminum, but the article “Thermal treatment of liquid crystal display panel scraps: The metals migration and potential environmental risk in solid residue” (Zhuang *et al*., 2019) drew attention for being in line with this research. In this research, the authors use heat treatment to investigate the transformation of ten metals on LCD screens (Cr, As, Al, In, Ni, Cu, Zn, Cd, Fe, Sn). This investigation demonstrated that Cr, Ni, In, Cu and Fe exhibit migration behavior from the solid phase to the gas phase, but by the graphs presented, aluminum demonstrated to be a stable compound (Zhuang *et al*., 2019). Finally, in the analysis of the author Liu, Y., it was noted that the author permeated issues related to sustainable manufacturing, CO2 mitigation, fly ash recovery, silicon recycling, energy consumption assessment, water recovery and reuse, among others. The article “Progress in research and application of non-ferrous metal resources recycling” (Guo *et al*., 2019) seemed to be in line with the research. In this research, Guo *et al*. (2019) prepare a review study on the cycle of non-ferrous metals, comparing the progress of recycling technology. Unfortunately, the article was published in a Chinese journal, in Chinese language, to which it was not possible to have access. Through reading the abstract, it is clear that the authors permeate the subjects of the “innovative researches of the Research Institute of Resource Recycling of Central South University on the green circulation of the" urban mine ", the clean recycling of rare metals, the improvement of the resource recycling process and the recycling of materials ". "Finally, the future development of the cycling of non-ferrous metal resources is prospected" (Guo *et al*., 2019).

CONCLUSION

Despite a large volume of documents initially presented, there was no complete validation of the initial set of keywords: “innovation + aluminum + recycling”. In other words, no innovations were detected in the aluminum recycling process, perhaps because these innovations are not declared as the main part for aluminum, and are included in other products, as in the case of LCD recycling (Zhuang *et al*., 2019), or simply because no significant attention has yet been paid to this process.

Regarding the research questions, it can be seen that for:

Q1 - What are the methods and / or tools used to promote improvements in the aluminum recycling process with a focus on the development of conductivity in aluminum alloys?

Only the article “Environmental friendly technology for aluminum electrolytic capacitors recycling from waste printed circuit boards” (Wang; Xu, 2017) presented a significant analysis on the results of aluminum recycling, indicating percentages of purity, but no article clearly addressed the recycling processes or even new technologies aimed at recycling this metal. Another issue can be inferred from this conclusion, that the aluminum recycling processes are being discussed within the traditional or alternative energy generation or transmission processes.

Q2 - Who are the main authors who have published on this topic in the last 5 years?

This research question was clearly discussed, considering that the authors were presented according to the pre-stipulated selection criteria and also analyzed 100% of each author's work in the period 2016-2020. This way we had: Zhang, Y, with 32 documents; Wang, Y, with 31 documents; Wang, J, with 29 documents; and Liu, Y, with 28 documents. As a suggestion for future work, it will be possible to seek the prospect of a recycling plant focused exclusively on aluminum and, as a consequence, the maximization of its use.

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