UTILIZATION OF THE LIFE CYCLE ASSESSMENT (LCA) METHOD TO EVALUATE THE ENVIRONMENTAL IMPACT OF ALKALI-ACTIVATED MATERIALS: A SYSTEMATIC LITERATURE REVIEW

Utilização do método de avaliação do ciclo de vida (ACV) para estudo de impactos ambientais em materiais álcali-ativados: Uma revisão sistemática de literatura

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Resumo

Os materiais álcali-ativados têm surgido, nos últimos anos, como um ligante eco eficiente alternativo que pode reduzir impactos ambientais acarretados pela produção de ligantes convencionais. Apesar disso, estudos de análises de impactos ambientais em materiais álcali-ativados ainda não são tão difundidos. O artigo apresenta uma revisão sistemática de literatura a respeito do uso do método de avaliação do ciclo de vida (ACV) para avaliar os impactos ambientais de materiais álcali-ativados. Uma metodologia de pesquisa foi proposta, a partir da definição de uma questão de pesquisa, e através da utilização da base de dados SCOPUS, selecionaram-se e analisaram-se artigos (2010 a 2023) diretamente ligados ao tema. Distribuição geográfica de publicações, análise de co-ocorrência de palavras-chave, levantamento de precursores e ativadores utilizados e quantificação de impactos ambientais estudados foram avaliados. Além disso, o impacto dos componentes de misturas álcali-ativadas e a emissão equivalente de CO_2 de algumas misturas reportadas por literaturas também foram discutidas. Misturas com diferentes tipos de precursores e ativações por potássio foram pouco exploradas em relação aos impactos ambientais incorporados. Análises de acidificação, eutrofização, toxicidade humana, ecotoxicidade aquática, depleção de recursos e depleção da camada de ozônio ainda possuem margem para estudos em trabalhos futuros.

Palavras-chave: Avaliação do ciclo de vida; Materiais álcali-ativados; Emissão de CO_2 incorporada; Aquecimento global; Impactos ambientais.

ABSTRACT

Alkali-activated materials have emerged in recent years as an alternative eco-efficient binder that can reduce the environmental impacts caused by the production of conventional binders. However, there is still a lack of studies analyzing the environmental impact of alkali-activated materials. This paper presents a systematic literature review on the use of Life Cycle Assessment (LCA) methodology to evaluate the environmental impact of alkali-activated materials. A research methodology was proposed based on the definition of the research question. Using the SCOPUS database, articles (2010 to 2023) directly related to the topic were selected and analyzed. The geographical distribution of publications, keyword co-occurrence analysis, evaluation of precursors and activators used, and quantification of environmental impact were evaluated. The impact of the components of the alkali-activated mixtures and the equivalent CO2 emissions of some mixtures reported in the literature are also discussed. Mixtures with different types of precursors and potassium activation have been poorly studied in terms of their environmental impacts. Analyses of acidification, eutrophication, human toxicity, aquatic ecotoxicity, resource depletion, and ozone depletion remain to be investigated in future studies.

Keywords: Life cycle assessment; Alkali-activated materials; Embodied CO_2 emission; Global warming; Environmental impacts.

1 INTRODUCTION

Ordinary Portland cement (OPC) is the world's most widely used construction material and its production process generates approximately 8% of global CO_2 emissions and 10% of global energy consumption (KUMAR DAS et al., 2022; BIERNACKI et al., 2017; HABERT et al., 2020). Considering this scenario, alkali-activated materials (AAMs) are considered alternative binders that have been more recently studied because of the benefits, mainly environmental, of this type of material when compared to OPC-based materials. This type of material can generate reductions of up to 80% in CO2 emissions compared with OPC production (DUXSON et al., 2007; DE GASPERI et al., 2021; LONGHI et al., 2020).

Life cycle assessment (LCA) and environmental impact studies of alkali-activated materials are crucial to more precisely determine the environmental benefits that this type of material provides, to make this material a feasible alternative to OPC-based binders. Furthermore, these studies make it possible to delimit the stages or materials involved in the production of alkali-activated mixtures that are responsible for the greatest environmental impacts related to global warming, water ecotoxicity, human toxicity, resource depletion, and ozone layer depletion, among others (ALHASSAN et al., 2023). This type of study has already been proposed by some authors for alkali-activated materials (MAHMOODI et al., 2023; ROBAYO-SALAZAR et al., 2018; ABDULKAREEM et al., 2021; RAMAGIRI and KAR, 2021).

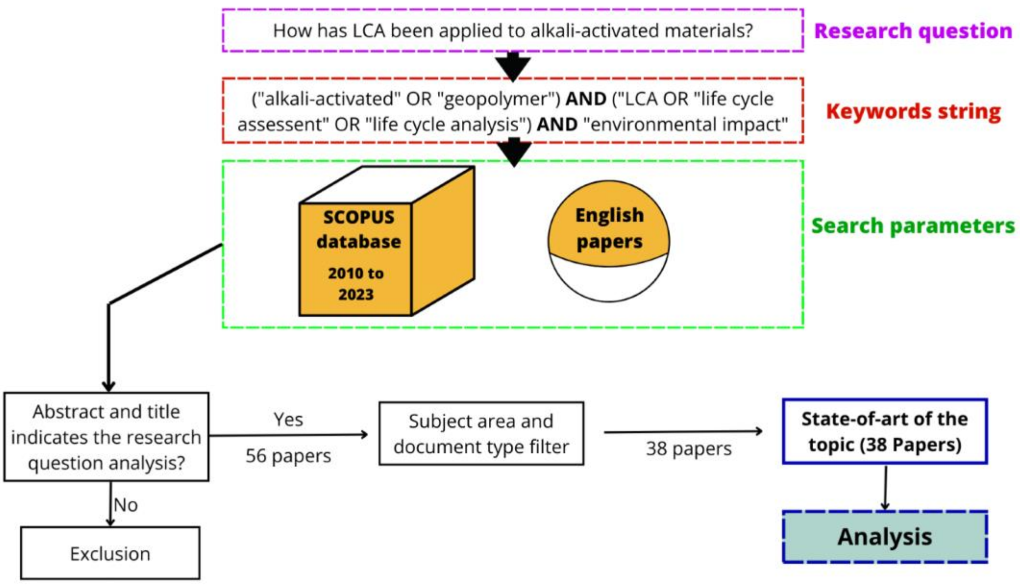
This article aims to conduct a systematic literature review (SLR) on the panorama of papers that conducted the Life Cycle Assessment (LCA) method to identify different types and intensities of environmental impacts for alkali-activated materials. This analysis will expose relevant indicators and provide information regarding this topic to assist and guide future studies.

2 RESEARCH METHODOLOGY

The research methodology adopted in this systematic literature review is summarized in the flowchart in Figure 1. The first stage of the methodology was to define the research question that would guide the types of papers to be analyzed. The research question chosen was "How has LCA been applied to alkali-activated materials?". The selected papers must answer this research question.

In the second stage, the keyword strings used in the research were determined. These keywords were ("alkali-activated" OR "geopolymer") AND ("LCA" OR "life cycle assessment" OR "life cycle analysis") AND ("environmental impact"). These keywords were chosen to limit the research to a specific topic. The search was conducted using the SCOPUS database, for English-language papers published between 2010 and 2023, to understand the panorama of publications and studies on the topic in the last 13 years.

Figure 1: Systematic literature review methodology.



Source: Author (2023)

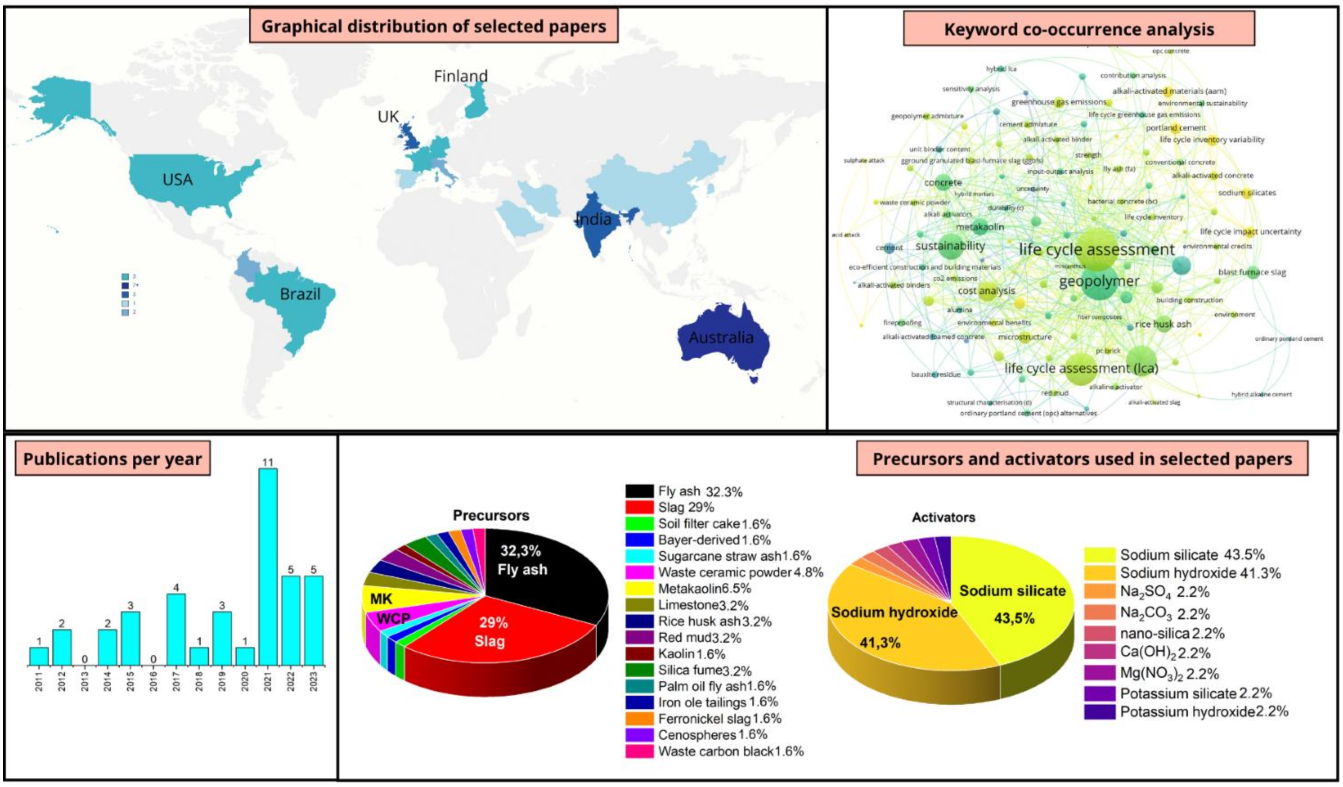
The initial search resulted in 56 papers which were analyzed on the basis of their title and abstract, to determine if these study parameters indicate possible analyzes that could answer the selected research question. Thus, 18 papers that were not related to the analyzed research proposal were excluded. Then, using the SCOPUS database, filtering was performed in terms of the subject area and type of document. The search was limited to articles from journals in the fields of study "Engineering" and "Materials Science" AND "Environmental Science". Based on this filtering process, 38 papers were selected for analysis.

3 SYSTEMATIC LITERATURE REVIEW

The 38 selected papers were analyzed according to their respective years and countries of publication. Keyword co-occurrence analysis was also performed using the VOSviewer software. The distribution of precursors and activators used in each of these studies was graphically organized. This information is summarized in Fig. 2. Australia (7), India (5), Brazil (3), Finland (3), the United Kingdom (5), and the United States (3) have the highest number of publications. Regarding the years of publication, there has been a large increase in the number of publications beginning in 2021 (11 papers). The keyword co-occurrence analysis highlighted words such as "life cycle assessment", "geopolymer", "sustainability", "concrete", and "cost analysis", and words referring to precursors such as "blast furnace slag", "rice husk ash" and "metakaolin". Such words indicate a direct relationship between the articles selected and the topic analyzed in this review.

The most commonly used precursors in the articles were slag (29%), fly ash (32.3%), metakaolin (6.5%), and waste ceramic powder (4.8%). Sodium-based activators (sodium silicate and sodium hydroxide) stand out, with other types of activators being slightly present.

Figure 2: Summarized analysis of selected papers: geographical distribution, publications per year, keyword co-occurrence, and precursors and activators used in the articles.

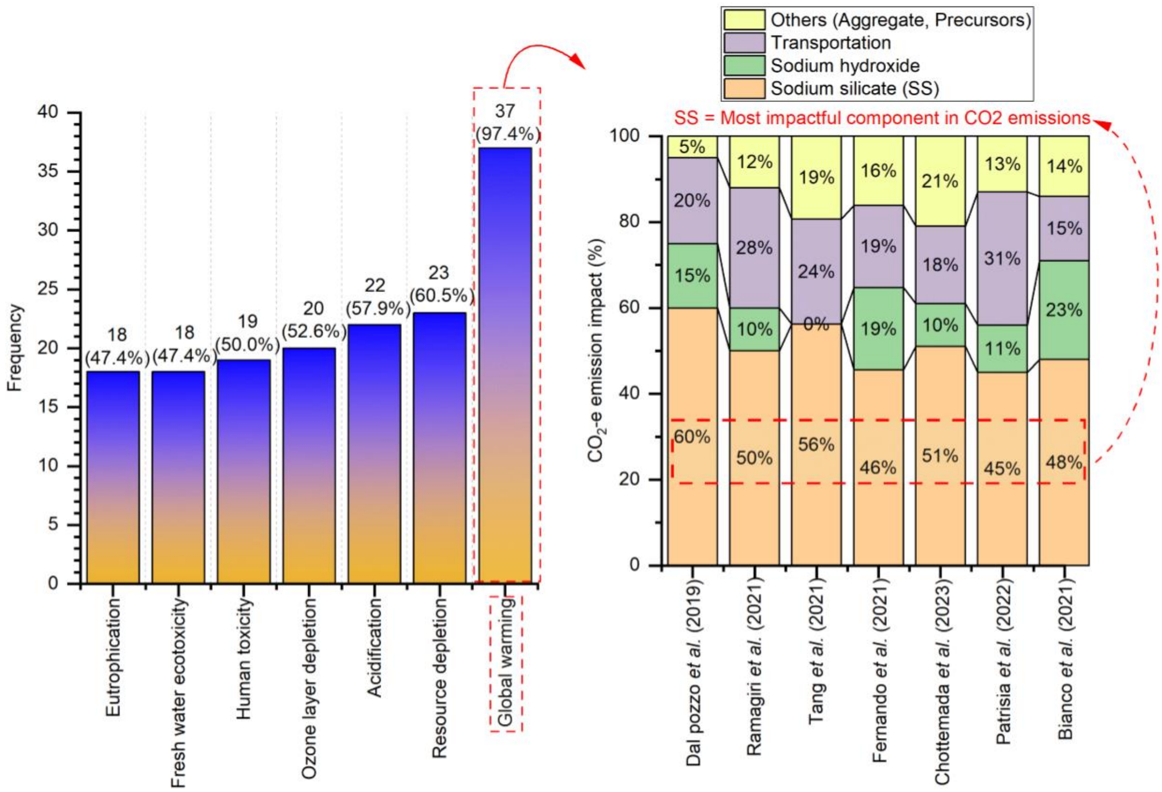


Source: Author (2023)

The papers were then analyzed to identify the environmental impacts most frequently covered in these reports. The types of impact were divided into "Global warming", "Resource depletion", "Acidification", "Eutrophication", "Ozone layer depletion", "Human toxicity" and "Fresh Water ecotoxicity". Fig. 3 shows the number of analyzes carried out to assess each of these impacts, with a strong emphasis on the study of global warming (97.4%), which is directly linked to CO_2 equivalent emissions from alkali-activated materials. The other impacts were assessed on a lower scale, in the range of 47% to 60% of the articles. This lack of assessment for other types of environmental impact may be directly linked to the availability of CO_2 emission-related information for materials. Information on other parameters may be scarcer, making it difficult to evaluate them. Despite this, further studies regarding the other environmental impacts listed are important and could be explored in future research.

Fig. 3 also shows details of the global warming study carried out by some authors, indicating the relative impact of each production process component on CO_2 equivalent emissions from AAMs. Sodium silicate stands out as the most impactful component in the analysis of CO_2 emissions among the articles selected, accounting for approximately 45 to 60% of the total emissions of alkali-activated mixtures. Such information is extremely relevant for assessing the viability of these materials because the quantities and types of activators used have a significant impact on this sustainable characteristic. Thus, the determination of environmental impacts requires a specific analysis for each mixture because of the existence of particularities in the activation parameters and mix design. The transportation required to produce materials and mixtures also plays a significant role in CO_2 equivalent emissions (15 to 30%).

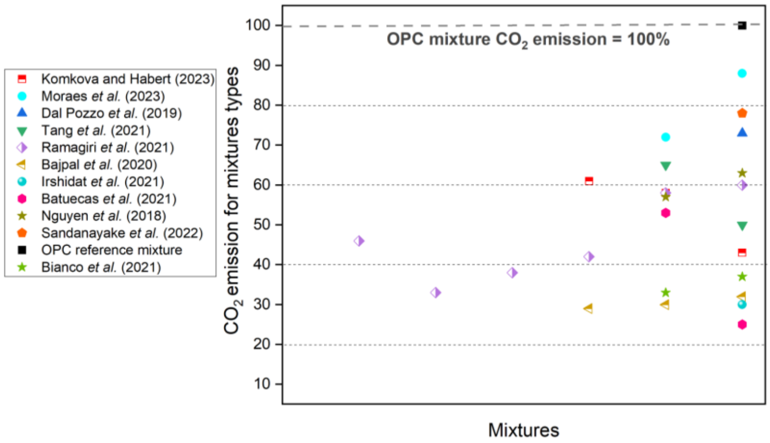
Figure 3: Frequency of LCA analyzes performed and impact of alkali-activated mixtures components in global warming.



Source: Author (2023)

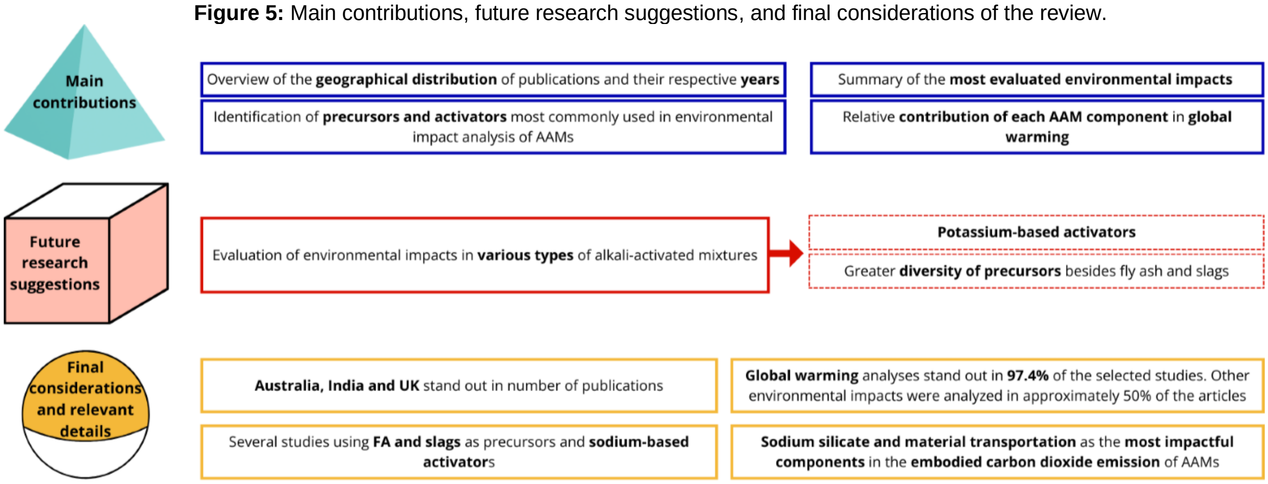
As shown in Fig. 3, the analysis of CO_2 emissions is extremely important when studying the environmental impact of alkali-activated materials. Figure 4 shows the relative CO_2 emissions of various alkali-activated mixtures from the selected papers. In this graph, the 100% limit corresponds to the equivalent emission of the OPC-based binders. This graph shows a lower equivalent CO_2 emission for alkali-activated materials when compared with OPC, and this benefit is essential for establishing this type of material as a sustainable alternative binder. The data indicate a maximum emission of AAMs corresponding to 86% (MORAES et al., 2023) of the CO_2 OPC equivalent emission, while most reports indicate even higher reductions in this emission, with a minimum value of 24% (BATUECAS et al., 2021). Importantly, these parameters vary greatly with mixing parameters, especially linked to activators, where sodium silicate is one of the main contributors to environmental impacts incorporated into alkali-activated mixtures (MAHMOODI et al., 2023; ROBAYO-SALAZAR et al., 2018). A summary of the contributions and relevant information in this review is shown in Fig. 5.

Figure 4: Equivalent CO_2 emissions for various types of AAMs.



Source: Author (2023)

Figure 5: Main contributions, future research suggestions, and final considerations of the review.



Source: Author (2023)

4 CONCLUSIONS

Alkali-activated materials have emerged as a great sustainable alternative to binders. Concerning the use of LCA as a method for measuring the environmental impact of alkali-activated materials, this systematic literature review led to the following conclusions and future research suggestions:

- A major focus is on sodium-based alkali-activated mixture environmental impact analysis, with the lack of this type of study for mixtures with other activation parameters.
- Lack of diversity of precursors used in the environmental impact analysis of AAMs.
- Australia, India, and the United Kingdom stand out in terms of the number of articles published on the issue studied.
- Global warming is the most studied type of environmental impact (97.4%). Other environmental impacts remain to be further studied and can be better explored in future research.
- Sodium silicate and transportation processes play significant roles in the equivalent CO_2 emissions of alkali-activated mixtures. The influence of these parameters on other types of environmental impact studies can be explored in future work.
- The selected studies show a reduction in CO_2 emissions for various types of alkali-activated materials compared with OPC-based binders. Despite this, it is important to perform specific analyzes for each mixture because small changes in the mixture parameters could significantly influence the environmental impact analyzes.

The application of the LCA method to improve the understanding of environmental impact parameters associated with alkali-activated materials is not yet widespread and provides very relevant information and insights into this type of material. Thus, this research aimed to raise and summarize important information to assist in future works.

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