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Environmental assessment of materials in preparing alkali-activated materials using bauxite residue

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Abstract. Aluminum is a highly produced metal globally. In the built environments alone, aluminum is known for its light weight and anti-corrosive properties and is a common choice of material in window frames, curtain walls, and light fixtures. The metal is processed from its oxide, alumina, the production of which releases a caustic byproduct known as bauxite residue (BR). BR is stored in massive reservoirs, however, due to the sheer volume of production, industries handling the material are reaching their storage limits. It is of high importance to research methods to valorize BR. Researchers have proposed a multitude of valorization methods, which include metal recovery from the byproduct, and using BR as raw material in production of another material. However, it is counterproductive to expend considerable amounts of energy and use excessive raw materials to manage utilization of BR. This study compared a method of valorization of bauxite residue with clay bricks. The method of preparing alkali-activated materials (AAM) with bauxite residue as a precursor was semi-quantitatively analyzed to compare the raw materials in the AAM with clay bricks. The materials were analyzed for climate change, ozone depletion, human toxicity, and aquatic ecotoxicity using OpenLCA software and the ecoinvent version 3.4 database. While the alkali activators possessed high values of the environmental impact when measured by the kilogram, the impacts were greatly reduced due to their small percentage in weight contained in the AAM. This study is the first stage of analyzing the environmental costs of valorizing bauxite residue. The AAM showed low environmental impact in material use when impacts of toxicity are considered. However, it displayed a higher climate change impact than that of clay bricks. Transport of raw materials to the preparation site played a significant role in the analysis. The next step is to compare the energy used in preparing AAMs.

1. Introduction

Aluminum is one of the most highly produced metals, displaying the largest growth rate amongst commonly used metals in the 21st century [1]. The material is woven into the fabric of almost every global industry, from aeronautical, marine, and electronic engineering to the production of beverage containers and daily household items. The metal is also used in the fabrication of solar panels and wind turbines, securing its consistent demand in a future using renewable energy [2]. A quarter of the total aluminum produced is used in the construction industry [3]. Its low weight, light-reflective surface, and corrosion-resistant properties render it a choice material in many architectural aspects – from decorative facades, window frames, and corrugated roofs to interior railings, staircases, and light fixtures [4].

Aluminum is produced using the Hall-Heroult smelting process, in which the aluminum oxide compound called alumina is electrolyzed. Alumina is produced by the Bayer process, in which the ore

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– bauxite – is dissolved in a caustic, high-temperature, and pressurized environment. The Bayer process releases a by-product called “bauxite residue” [5].

Bauxite residue (BR) is rich in minerals, getting its characteristic red hue from a high percentage of iron compounds present in its composition. In its raw state, the material possesses considerable percentages of titanates, iron compounds, feldspathoids, and moisture. It is also corrosive due to its high alkalinity. The composition and alkalinity possessed by bauxite residue is dependent on the location from where the bauxite is mined and industrial processes used to refine the alumina [5, 6]. In other words, properties possessed by bauxite residue vary greatly based on where the material is produced.

Bauxite residue is conventionally disposed of by chemically treating the material before holding it in dams that cover large areas of land. Once the residue fills the holding, the land undergoes a neutralization process spanning five to twenty years, after which the land can be reused for vegetation growth [7]. The current global stockpile for bauxite residue amounts to four billion tons, straining the capacities of containment facilities worldwide [8]. Every year, an estimated 150 million tons of bauxite residue is produced, with a reutilization rate of 2-3% [9]. Using this product stream as a raw material for another industry is integral in shifting the linear extraction-to-disposal process to a circular process in the aluminum industry.

Processes that manage the valorization of bauxite residue can be broadly classified into three to four categories: material recovery from bauxite residue, use of bauxite residue as raw material for another product, and utilization of bauxite residue in chemical processes. Bauxite residue is rich in minerals such as scandium, iron, and titanium, leading to research in extraction processes of these minerals. Increasing efficiency of the extraction process to maximize metal recovery is the major challenge faced in this area of research [10]. In another area of research, possibilities for the use of bauxite residue as a raw material in cement production, alkali-activated materials, and ceramics are explored, due to the aluminosilicate species present in the material’s composition. The low reactivity of bauxite residue due to its high crystallinity is the major hurdle researchers face to transform bauxite residue in the construction industry [11, 12]. Finally, bauxite residue displays adsorbent properties that might be instrumental in the development of wastewater and gas treatment technologies [13].

While there are a significant number of studies in the development of proof-of-concepts, few methods have progressed to being a part of industrial practice. To take a proven valorization method from the laboratory to industry, economic and environmental assessments are necessary. Additionally, due to the variance in composition of bauxite residue depending on its source, applications and assessments of its valorization would differ based on the production and processing location [6].

Under the category of the use of bauxite residue as a raw material for another product, there is research interest in using bauxite residue as a precursor in alkali-activated materials (AAMs). AAMs broadly refer to cement-like binders that form when an aluminosilicate-rich material, such as metakaolin, fly ash, or blast-furnace slag, is dissolved in an alkaline medium. AAMs garnered research interest since their production requires temperatures between ambient and 100°C and they develop strength comparable to cement [14]. These materials have applications ranging from use as an alternative to certain building materials, like cement and brick, in the construction industry, to displaying adsorbing properties in wastewater management [15, 16].

Studies show that bauxite residue can be incorporated as a precursor in alkali-activated materials, with the product reaching comparable strength and durability of other materials used in conventional building practice [6]. Bauxite residue is often chemically or thermally treated to increase its reactivity. However, not many studies provide information on the environmental and economic assessments of these valorization methods.

The objective of this paper is to do a preliminary environmental impact analysis of the materials that would be required to prepare an alkali-activated material using bauxite residue. This information varies greatly depending on location; hence the assessment is localized to studies done in Quebec, Canada. The research questions asked in this paper are:

1) Are there materials used in the preparation of the AAM that have a larger environmental impact than in the usage of conventional clay oven-baked bricks?

2) How do we quantify the limits of certain raw materials that may increase the environmental impact of the product without having a large database available?

These research questions are answered by identifying products of concern in the preparation of bauxite residue based AAM using a cradle-to-site life cycle assessment with the ReCiPe method. Data on environmental factors such as climate change, aquatic ecotoxicity, and ozone depletion were collected using ecoinvent version 3.4 database [18]. The bauxite residue based AAM is compared to oven baked clay bricks. This study is not intended to be a complete life cycle analysis yet, and the scope of the study is limited to a semi-quantitative stage intended to be used for future decisions on the optimization of the alkali-activated material.

2. Literature review

To understand the requirement of environmental assessments in the use of bauxite residue in AAMs, a literature review was conducted in January 2024, using the keywords “alkali-activated materials” OR “geopolymers” OR “inorganic polymers” AND “bauxite residue” OR “red mud”, on the following search engines: Science Direct, Scopus, and Springer. The review was limited to papers published in the English language and between the years of 2014 to 2024. Fifty-six research papers published in a span of ten years were divided into categories depending on the objectives of the research. The research papers were classified based on first, reading the title and abstract, and then, reading the full paper. The classification of research is defined in the following terms:

1. Preparation: Research papers that have developed a novel material, or product, or have optimized the process for developing the material.
2. Properties: Research papers that focus on characterization of the material and comparing properties relevant to the application of the material to standardized values.
3. Chemistry: Research papers that study undergoing reactions, kinetics, and development of intermediary species in the material.
4. Life cycle thinking: Research papers that analyze environmental or economic factors in the material and energy usage in the process of preparation, application, or duration of the material’s life.

The division of research is displayed in Figure 1, showing over half of the research in the domain focused on the preparation of AAMs using bauxite residue. Only 5% of the research papers were focused on the environmental and economic assessment of the product. Hence, a need to address this gap is visible.

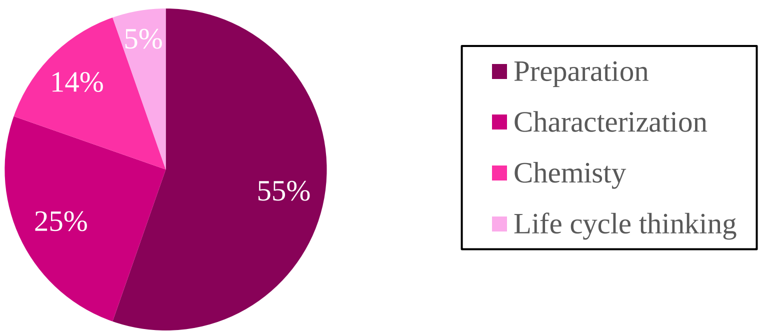

Figure 1: Pie-chart displaying percentage of research papers published over the last ten years (2014-2024) in the domain of using bauxite residue in preparation of alkali-activated materials.

The disproportionate number of papers that encompass the preparation category can be explained by the fact that this area of research is recent, with the first publications dating back twelve years [19, 20]. Most research over the next decade was dedicated to improving the strength of the AAMs to be comparable to that of cement and other building material applications while increasing the ratio of bauxite residue in the composition of AAM. However, studies have achieved the ASTM standard for cementitious materials in the construction of over 28 MPa [16, 21, 22]. New research is directed to incorporating the material in industrial applications and assessing its economic and environmental viability [6].

3. Methodology

A recently published process to prepare high strength AAMs out of bauxite residue and fly ash used mechanical milling to mix raw filter-pressed bauxite residue with the alkali activators [16]. Bauxite residue possesses the challenging property of a crystalline nature that leads to low reactivity. To combat this, some studies use thermal or chemical treatments to transform bauxite residue into an amorphous solid before the material as a precursor [12, 23, 24]. However, in the chosen method for this study, the bauxite residue is used with no pre-treatment, possibly reducing the energy required in processing [16]. In the alumina refinery plant, the bauxite residue is filtered and dewatered until the moisture levels are reduced to 25-35% before the residue is stored in a dry stacking facility [25]. This raw and filtered bauxite residue is used as the major raw material for the AAM, with over 70% in weight in composition. The process of valorizing the raw filter-pressed bauxite residue into an AAM is explained in Figure 2.

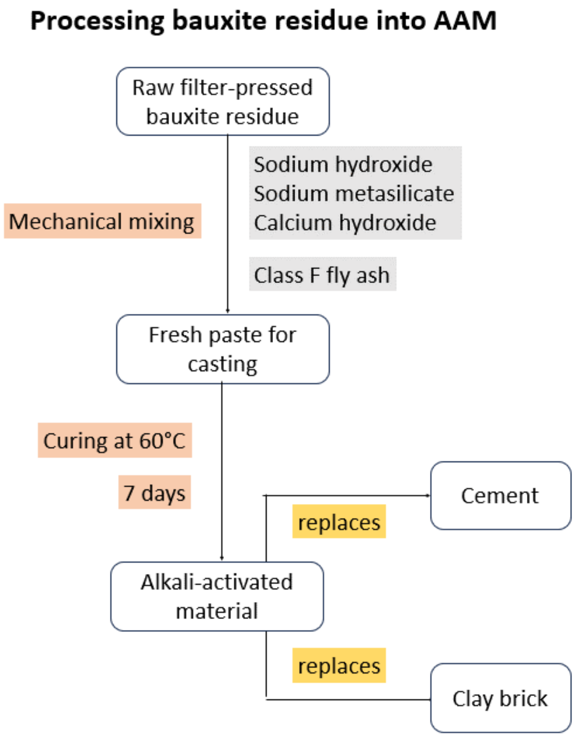

Figure 2. Preparation process flow sheet of AAM.

There are multiple potential applications of the AAM as described by the study, but the material is meant to replace clay bricks and cement in concrete applications [16]. This study focuses on the application of the AAM in place of clay bricks. The raw materials used to prepare the AAM and clay bricks were identified, after which an analysis was done [16, 17]. After identifying the parameters, data on the environmental impact was collected using OpenLCA software and ecoinvent version 3.4 database [18].

The scenario considered for defining the functional unit and system boundaries is to prepare a wall for a building in Montreal, Quebec. The mass of the total product needed is 100 kg. Mortar is used in both clay and AAM-based brick, and hence is not considered in the analysis. AAM and clay bricks are compared only using a mass allocation scenario.

The impact for fly ash was calculated using references from literature and ecoinvent processes of hard coal in Canada [26]. Taking only mass allocation into account, fly ash production accounts for 9.3% of preparation and combustion impacts of coal mining. This means production of 1 kg of fly ash has the same impact as mining of 0.093kg of coal and that fly ash production is 9.3% the energy of burning coal. One kilogram coal equivalent corresponds to a value specified as 7,000 kilocalories (7,000 kcal ~ 29.3 MJ ~ 8.141 kWh) and thus, the calorific value of hard coal [27]. Hence, 9.3% of 7000 kcal is 651 kcal, which is used for energy consumption in fly ash.

The bauxite residue from bauxite digestion process illustrates the impact the material has by existing and its need to be neutralized to limit its environmental impacts. The alkali activators and clay production processes used were directly available in the ecoinvent database. The masses of components to produce the AAM are based on the work of Mare, M.D. and C.M. Ouellet-Plamondon, 2023 [16].

To consider the transport step of the materials, the freight, light commercial vehicle process is considered. The building to be used for the scenario is the École de technologie supérieure (ETS), at the address 1100 R. Notre Dame O, Montréal, QC H3C 1K3 in Canada. The transport distances are shown in the Table 1.

Bauxite residue is transported from Rio Tinto Jonquière complex, at 1955 Bd Mellon, QC G7S 4L2 in Canada. Fly ash is transported from the Belledune Generating Station, at 1558 Main St, Belledune, NB E8G 2M3. Alkali activator additives for AAM are present on site as the building is next to the laboratory where the AAM will be prepared. Hence transport distance is not considered for the alkali activators. Clay bricks of standard C62 is transported from Novabrik International Inc., at 3715 Bd Saint-Jean-Baptiste #205, Riviere-des-Prairies—Pointe-aux-Trembles, QC H1B 5V4.

Table 1. Transport data of materials

Materials	Distance by road (km)	Weight (t)	Transport volume (t.km)
Bauxite residue	477	0.077	36.729
Fly ash	837	0.0145	12.137
Clay bricks	31.5	0.100	3.15

The ReCiPe method with Midpoint E was used to calculate the environmental impact on climate change, freshwater ecotoxicity, marine ecotoxicity, ozone depletion, and human toxicity, as it tends to have more relevant indicators for those categories [28].

4. Results

The life cycle analysis was conducted on clay bricks and the alkali activated material. Figure 3 compares the impact factors of brick with the AAM (named as RM-AAM, or "residue-mixed alkali activated material", in the figures) – first with the transport flow added, and then without. It shows that the use of transport significantly increases the impact factors in every category. Figure 4 shows the different impacts of each component used in RM-AAM production in each category displayed in Figure 3. In Figure 4, the labels on the X-axis refers to the constituents of the RM-AAM – the raw bauxite residue material (RM), fly ash (FA), anhydrous calcium hydroxide ($Ca(OH)_2$), sodium hydroxide flakes (NaOH), and sodium metasilicate ($NaSiO_3$).

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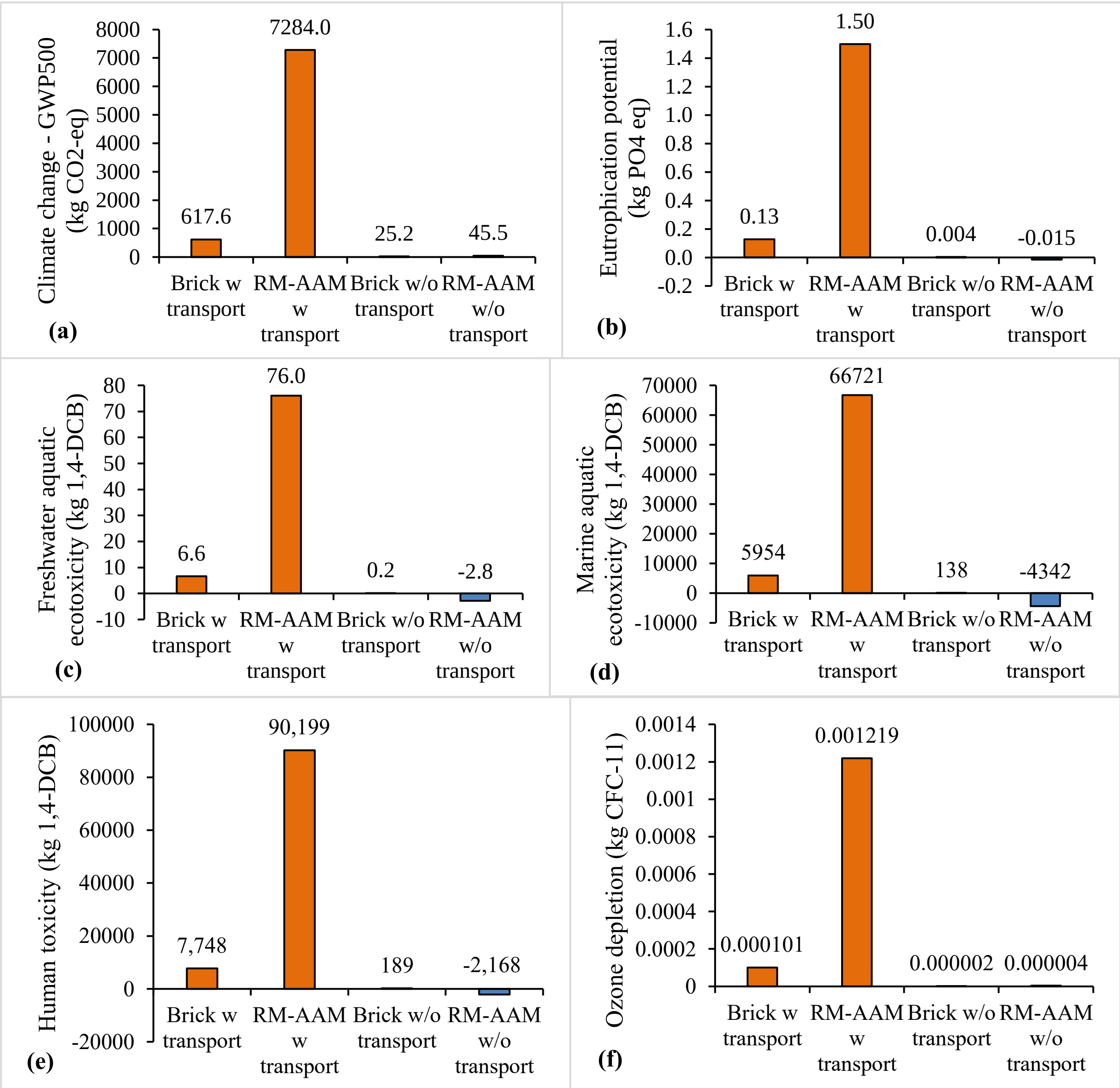

Figure 3. Comparison of impact factors between brick and RM-AAM with and without transport phases for climate change (a), eutrophication potential (b), freshwater aquatic toxicity (c), marine aquatic toxicity (d), human toxicity (e) and ozone depletion (f).

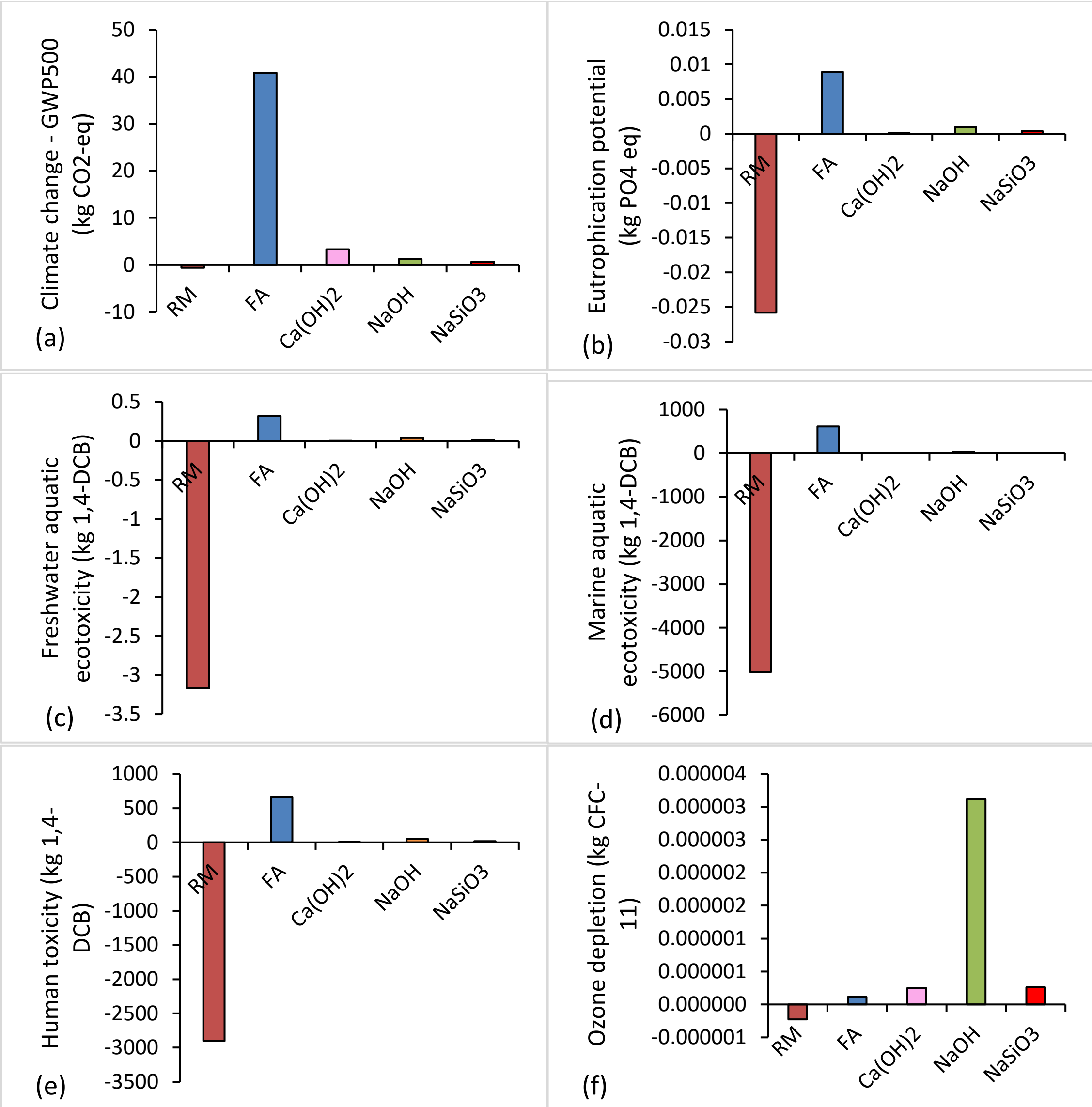

Figure 4. Comparison of impact factors of components of RM-AAM for climate change (a), eutrophication potential (b), freshwater aquatic toxicity (c), marine aquatic toxicity (d), human toxicity (e) and ozone depletion (f).

All graphs in Figure 3 display how importantly transport affects the impact factor of both RM-AAM and brick use. Production of bauxite residue and fly ash occurs in industry, at a considerable distance from cities and towns with construction activity, increasing the overall impact of transport for RM-AAM production. As for the bricks, the scenario used showed a nearby production facility, limiting its total impact, despite having a heavier cargo. In total, the impact factor of transport for RM-AAM and bricks accounts for 95% up to 99% of all impact factors, requiring a scenario without transport to better understand the pros and cons of RM-AAM compared to bricks.

In the case of Figure 3 (b, c, d, e), the preparation of RM-AAM has a negative impact, showing that it helps reduce its impact for eutrophication along with aquatic and human toxicity. The negative value is observable in Figure 4 and explainable by the process used in the ecoinvent database, called treatment of bauxite residue by neutralization. It subtracts the impact factor potential of bauxite residue from the environment by limiting its harmfulness to the environment. As the use of bauxite residue in the AAM process intends to stabilize BR and make it usable, this treatment appears to be justified.

However, in Figure 3 (a, f), it shows that the impact of RM-AAM on climate change and ozone depletion is nearly double that of clay brick production. Based on Figure 4 (a, f), the fly ash production is the main cause of the increase of the climate change factor, while the alkali activators affect the ozone depletion factor the most. The other graphs in Figure 4 also demonstrate that fly ash is the main component that increases the impact factor in the remaining categories, but the use of a high amount of bauxite residue helps reduce the overall environmental impact.

In fly ash production, heating the coal causes around 90% of its impact in all categories, with coal extraction causing the last 10%. Fly ash was not considered a byproduct in this study. However, if recycled fly ash is used, the AAM would have reduced environmental impact than clay bricks in every impact category. Meanwhile, the impact factors of alkali activators are low in general due to their small mass percentage in AAM.

5. Conclusion

Methods to valorize bauxite residue by binding the material into an alkali-activated material has been a growing area of research over the last 10 years. However, most of the literature concentrates on preparation and applications of the bauxite residue based AAM, and few studies have been done on assessing the environmental impact of the material. This assessment is important as it is a step in taking the material from the laboratory to industry. This study, focusing on the initial stage of the LCA, found that the AAM can reduce the impact of bauxite residue on the environment. When compared to brick, the AAM had higher impacts on the environment due to transportation of the raw materials. Hence, an area of concern for future study is optimizing the transport of raw materials for the preparation of AAMs, for example, by utilizing a part of the alumina processing plant to prepare AAMs. This might reduce the overall effect of transportation, as the alumina processing plant might also already possess the alkali activators required. It would also be worthwhile to either use recycled fly ash, or find an alternative for the AAM production, as fly ash appears to be the major bottleneck to its overall impact, along with the fact that it is needed in many other applications, most notably cement production.

The binding of bauxite residue in an alkali-activator shows promising results and this study highlights areas of concern that can be considered while optimizing the material for industrial use. Another option for its development would be to improve its properties and applications in other sectors, such as a medium for soil remediation, an adsorbent for wastewater treatment, as a competing product to expanded clay, or to be recycled via rare earth extraction.

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