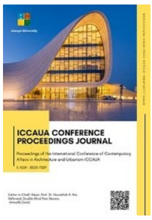

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Mechanical and Environmental Performance of Iron ore Tailing-based Geopolymers

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Abstract

Recent studies show iron ore tailings IOT possibilities as a sustainable substitute in geopolymer production. With an estimated 1.2 billion tons stored in tailings dams worldwide each year, iron ore tailings disposal poses significant environmental challenges. These tailings occupy land, polluting soil and water, and pose a risk of dam failure. Geopolymers, commonly known as sustainable replacements for conventional concrete and reductions in cement usage, are one of the most important sources of CO_2 emissions. Despite the emphasis on the sustainability of IOT-based geopolymers, most articles only focused on mechanical aspects and haven't analyzed environmental aspects. This article addresses this research gap by examining the mechanical properties, durability, and environmental performance of IOT-based geopolymers via life cycle assessment. Results reveal that including IOT in geopolymers increases their compressive strength, up to 50 MPa, and improves. LCA results show the better performance of sodium silicate and sodium hydroxide compared to potassium silicate and potassium hydroxide.

Keywords: Iron Ore Tailing; Geopolymer; Mechanical Properties; Durability; Life Cycle Assessment.

1. Introduction

The geopolymer term, first introduced by French scientist Joseph Davidovits in 1970s to describe a new class of mineral binders formed based on the alkaline activation of aluminosilicate-rich materials . It is often positioned as a sustainable alternative to OPC-based concrete due to its lower carbon footprint and excellent durability propertie (Scrivener et al., 2018). Unlike traditional cementitious binders, which rely on the hydration of calcium silicates, geopolymer is based on the polymerization of silicon and aluminum oxides derived from industrial by-products such as fly ash, metakaolin, and slag. This innovative material has since gained increasing attention for its mechanical performance, durability, and, most notably, its sustainability potential in modern construction (Davidovits, 1991).

The versatile properties of geopolymers enable their use across various fields. In the construction industry, they serve as sustainable alternatives in the production of concrete, masonry units, tiles, and insulation systems, demonstrating high strength and durability under aggressive environmental conditions(Sbahieh et al., 2023). Their high thermal stability makes them suitable for fire-resistant applications such as panels and protective coatings, which are crucial in infrastructure subjected to high-temperature exposure(Lahoti et al., 2019). In environmental management, geopolymers are effective in immobilizing hazardous and radioactive wastes, thanks to their dense, stable matrix (Wang et al., 2023). They also play a significant role in the rehabilitation of corroded structures, acting as coatings and repair mortars due to their low permeability and chemical resistance (Castaneda-Lopez et al., 2020).

The environmental advantage of geopolymer material extends beyond carbon mitigation. Its ability to repurpose industrial and mining wastes aligns with circular economy principles. Also, recently, the principle of the best available technique (BAT) has been introduced for the safe and principled management of tailings which involves minimizing the volume of tailings produced in the first stage and, in the second stage, maximizing opportunities for recycling and reusing tailings (Khezerloo et al., 2024). This significantly contributes to waste valorization and environmental preservation(Ye, 2022). Mining tailings, especially iron ore tailings (IOT), present serious environmental and safety risks when not properly managed. These tailings often contain fine particles that can contaminate soil and groundwater and are usually stored in large dams, which pose a risk of catastrophic failure. Additionally, tailings disfigure natural landscapes and reduce land usability(Ferreira et al., 2022).

The production of geopolymers involves a multi-step process beginning with the selection of aluminosilicate-rich materials such as fly ash, metakaolin, and slag ,known as precursor. The effectiveness of geopolymerization depends significantly on the choice and characteristics of both the aluminosilicate precursors and the alkaline activators. They serve as the fundamental source of silicon (Si) and aluminum (Al), which are the primary building blocks of the geopolymer network. Upon dissolution in a highly alkaline environment, these oxides participate in the polymerization process to form sodium or potassium aluminosilicate hydrate (N-A-S-H or K-A-S-H) gels(El Alouani et al., 2024). Reusing IOT as raw material in geopolymer synthesization could mitigate the environmental hazards and offer economic benefits when used in geopolymer concrete by reducing raw material costs in the construction sector(Ferreira et al., 2022). On the other hand, IOT often contains significant amounts of silica and iron oxides, making it chemically suitable for geopolymer synthesis when blended with alumina-rich materials..

The highly alkaline environment is produced using alkaline solutions, commonly sodium hydroxide and sodium silicate, which initiate the dissolution of silicon and aluminum species and facilitate the subsequent polycondensation into a gel matrix (Siyal et al., 2024). The most commonly used activators are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), though potassium-based alternatives are also used for specific performance objectives(Wang et al., 2019). (Wang et al., 2019). Sodium silicate, often used in conjunction with NaOH. The ratio of sodium silicate to sodium hydroxide (commonly referred to as the silicate modulus) is a critical parameter that influences the setting time and strength of the final product (Siyal et al., 2024). Potassium hydroxide (KOH) and potassium silicate are viable alternatives to sodium-based activators, especially in high-temperature applications due to their ability to produce thermally stable gels(Cong & Cheng, 2021).

Proper mixing ensures uniform reaction, while curing, at ambient or slightly elevated temperatures, allows the geopolymer network to harden and develop its characteristic mechanical and chemical properties. A shematic process that obtain from (Wang et al., 2023) showed in figure 1.

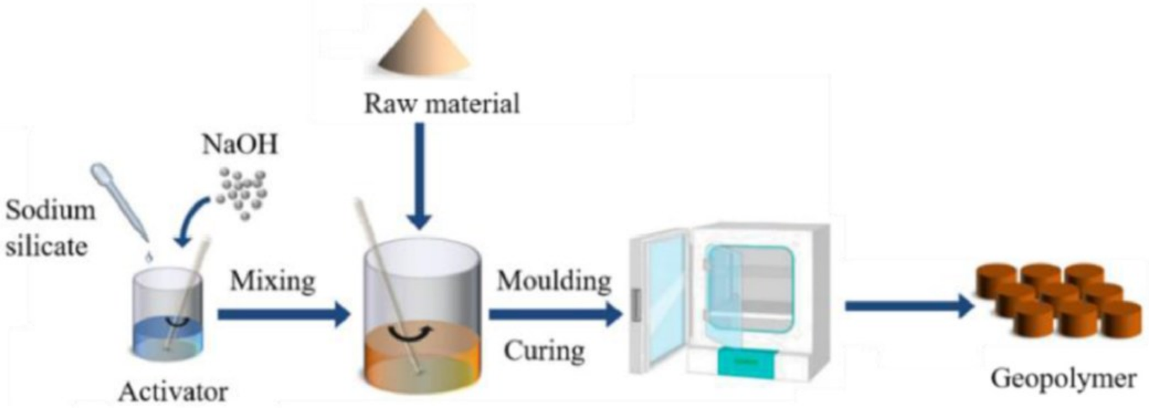

Figure 1. a shematic process of geopolymer production (Wang et al., 2023).

Curing conditions is another important parameter in the production of geopolymers. geopolymers often require specific thermal environments to activate and stabilize their chemical structure, especially during early-stage reaction kinetics (Siyal et al., 2024). The curing temperature, duration, and humidity directly influence the extent of geopolymerization, development of the aluminosilicate gel, and final material performance. Elevated-temperature curing,typically in the range of 40 °C to 80 °C,is widely used, especially for low-calcium precursors like fly ash (Wang et al., 2019). For high-calcium systems, such as those incorporating slag or blended binders, ambient curing may suffice due to the presence of reactive Ca^{2+} ions that promote additional C-A-S-H gel formation even at room temperature. This offers a more energy-efficient alternative for structural applications and broadens the range of field implementations (Sbahieh et al., 2023).

Humidity control is also critical. In dry environments, insufficient moisture can hinder the ongoing dissolution of precursors and lead to incomplete geopolymerization. Conversely, moist curing helps retain water within the matrix, allowing the reaction to progress and minimizing shrinkage(Lahoti et al., 2019). Sealed or steam-curing conditions are sometimes employed to balance hydration and prevent drying-related defects during the critical early phases.

Recycling and reuse of these tailings is one of the emerging methods that, alongside the circular economy and BAT principle, can be used to improve sustainability and reduce the volume of tailings in mines and behind tailings dams. Given the necessity to develop new and sustainable materials for the construction industry and the high availability of IOT waste, this work aims to assess current research results regarding using IOT as a precursor in geopolymer production and assessing its mechanical and environmental advantages.

2. Material and Methods

The literature review has been performed on the Scopus database, and mechanical properties, materials used, curing methods, and other related features have been gathered and analyzed. For selecting the articles whose environmental impacts would be assessed, the focus has been on the articles published past five years. After gathering, the articles were filtered, and three articles were selected for LCA. For conducting LCA, SimaPro software, version 9.3.0.2, has been used. The LCA study is based on the instruction of ISO 14040 and ISO14044 and the ReCipe 2016 impact assessment method has been used.

2.1. Literature Review and Data Collection

Publish or Perish software (Harzing, 2007) has been utilized in this study for finding articles. The key words in the search were geopolymers and IOT, with the exclusion of brick and ceramic. For environmental assessment, the most common types of geopolymers have been selected. The selection was based on the compressive strength, between 20 to 50 MPa, and two other precursors used in geopolymers, fly ash and metakaolin. Fly ash is widely utilized due to its favorable spherical morphology, low carbon content, and high reactivity. It offers a balanced ratio of silica to alumina, promoting the formation of a dense geopolymer gel (El Alouani et al., 2024). Metakaolin, a calcined form of kaolinite, is prized for its high purity and consistent reactivity, making it suitable for high-performance and precision applications (Vizureanu, 2023). After filtering, only three articles were in the scope of this study,Lameira et al, Lorenzini et al and Wang et al (Lameiras et al., 2023b), (Lorenzini et al., 2023), (H. T. Wang et al., 2024).

2.2. Data Extraction

Mix design of selected articles extracted manually by reading the articles carefully, finding the optimum mix design, calculating the percentage of each material (for solutions, often with the molar weight and ratios), and then scaling the weight of each material for a mix design of 1 ton. The mix design of each article is presented in Table 1.

Table 1. Mix Designs.

Wang-2024 (per 1 ton of geopolymer)		
Material	Amount	Unit
Fly Ash	476	Kg
Iron Tailing	200	Kg
Sodium Silicate	87.5	Kg
Sodium Hydroxide	62.5	Kg
Water	183	Kg
Lamires-2023(per 1 ton of geopolymer)		
Material	Amount	Unit
Kaolin	220	Kg
Iron Tailing	330	Kg
Sodium Silicate	162.5	Kg
Sodium Hydroxide	112	Kg
Water	175.5	Kg
Energy	440	MJ
L.Lorenzini-2023 (per 1 ton of geopolymer)		
Material	Amount	Unit
Kaolin	375	Kg
Iron Tailing	125	Kg
Potassium Silicate	163	Kg
Potassium Hydroxide	140	Kg
Water	198	Kg
Energy	1125	MJ

2.3. Life Cycle Assessment

The goal of this LCA study is to compare and find the environmental hot spots in the three mix designs of geopolymers, and the scope of the study is gate-to-gate. As mentioned earlier, SimaPro software, version 9.3.0.2, and for the database, Ecoinvent version 3.8, have been used. The inventories are mixed designs in Table 2. All the materials were available in Ecoinvent except potassium silicate, so the proxy data must have been used.

In Life Cycle Assessment (LCA), proxy data refers to information used in place of missing or unavailable specific data, often to represent similar processes or materials. The most common methods for selecting proxy data include choosing datasets with similar production technologies, chemical composition, or functional performance. The existing datasets may also be adjusted, like the data from Ecoinvent, by modifying input amounts, energy use, or emissions. When used carefully and transparently, proxy data helps maintain the completeness and relevance of the assessment while managing data gaps effectively (Finnveden et al., 2009; Weidema et al., 2013).

In this research, the proxy was selected based on similar production technologies; the same method has been used by (Roux et al., 2024). Potassium silicate is typically produced by fusing high-purity silica sand (SiO_2) with potassium carbonate (K_2CO_3) in furnaces at temperatures ranging from 1400°C to 1500°C. This high-temperature reaction results in the formation of a molten potassium silicate glass, which solidifies upon cooling (Novotny et al., 1990). Similarly, sodium silicate is produced by melting silica sand with sodium carbonate (Na_2CO_3) in furnaces at approximately 1400°C. The resulting molten sodium silicate is cooled to form a glass, which can be further processed into liquid form by dissolving in water. This fusion method is the most common route for commercial sodium silicate production (EPA, 2023).

Considering the main difference between the production of sodium silicate and potassium silicate is the replacement of sodium carbonate with potassium carbonate and the amount of silica sand and potassium carbonate needed, the amounts have been defined based on the stoichiometry calculations, and sodium carbonate has been replaced with potassium carbonate. The impact assessment method used in this study is ReCipe2016 Midpoint(I). Table 2 represents the impact categories of ReCipe2016 Midpoint(I) impact assessment method (ReCiPe, 2016).

Table 2. impact categories of ReCipe2016 Midpoint(I).

Midpoint	**eq unit**
Climate Change	kg CO_2
Ozone Depletion	kg CFC-11
Terrestrial Acidification	kg SO_2
Freshwater Eutrophication	kg P
Marine Eutrophication	kg N
Terrestrial Ecotoxicity	kg 1,4-DCB
Freshwater Ecotoxicity	kg 1,4-DCB
Marine Ecotoxicity	kg 1,4-DCB
Human Carcinogenic Toxicity	kg 1,4-DCB
Human Non-Carcinogenic Toxicity	kg 1,4-DCB
Particulate Matter Formation	kg $PM_{2.5}$
Ionizing Radiation	kBq Co-60
Photochemical Ozone Formation	kg NMVOC
Water Consumption	m^3
Land Use	$m^2 \cdot year$
Fossil Resource Scarcity	kg oil
Mineral Resource Scarcity	kg Cu

3.results

The key elements, including SiO_2 (silicon dioxide), Fe_2O_3 (iron oxide), and Al_2O_3 (aluminum oxide), play a significant role in determining the reactivity of the tailings in geopolymerization. The SO_3 content, as noted in several studies like (Wei, 2023) and (Zhang et al., 2025), influences the setting time and strength development of geopolymer concrete. Loss on ignition (LOI) is indicative of the material's moisture content and organic matter, with low LOI being preferable for geopolymer applications, as excessive moisture or organic impurities may hinder the formation of the geopolymer network. Considering the rational amount of abovementioned oxides in the IOTs sample around the world, which is observed in table 3, for the SiO_2 range between 25-90 percent and the Al_2O_3 range between 1-24 percent, it's obvious that IOT could be used as reactive or even nonreactive material in the production of the geopolymer.

Table 3. chemical composition (wt.%) of iron tailings from various sources

	%							
State, Country	**SiO_2**	**Fe_2O_3**	**Al_2O_3**	**CaO**	**MgO**	**SO_3**	**LOI**	**Source**
Hebei, China	48.1	7.08	6.97	8.36	25.53	26	-	(Zhan et al., 2024)
Hebei, China	75.1	7.58	6.58	3.01	42.2	34	-	(Li, 2025)
Yunnan, China	45.07	24.92	13.38	6.91	2.47	-	-	(Ning, 2025)
Karnataka, India	26	41	21.6	0.44	59	-	7.27	(Hameed, 2024)
Pará, Brazil	90.38	14.12	0.42	-	-	-	-	(Vieira, 2024)
Liaoning, China	87.65	5.72	0.81	1.87	1.81			(Zhao, 2024)
Odisha, India	24.9	32.8	23.9	0.2	0.6	0.01	<0.01	(Subramanian et al., 2024)
Shaanxi, China	62.56	5.65	7.53	8.46	8.19	0.25	2.26	(Huang, 2024)
Shaanxi, China	58.55	13.89	12.82	4.24	3.25	-	-	(T. Wang et al., 2024)
Minas Gerais, Brazil	71	23	3	0.04	2	0.18	-	(Prates et al., 2023)
Jiangsu, China	35.5	18.3	5.5	12.4	21.4	3.1	-	(Wei, 2023)
Minas Gerais, Brazil	86.25	11.89	0.43	0.57	-	-	-	(Ferreira et al., 2022)
Minas Gerais, Brazil	84.66	13.75	0.77	0.03	-	-	0.28	(Mazzinghy, 2022)
Minas Gerais, Brazil	84.7	13.8	0.8	-	-	-	-	(Figueiredo, Silveira, et al., 2021)
Minas Gerais, Brazil	83.09	15.36	0.6	0.02	<0.1	-	0.51	(Figueiredo, 2021)

So, IOT with these exceptional oxide components could act as a primary source of silica (SiO_2) and alumina (Al_2O_3), which are fundamental to the geopolymerization reaction. When combined with alkaline activators such as sodium hydroxide (NaOH) or sodium silicate (Na_2SiO_3), these components dissolve and reorganize into a geopolymer network. (do Carmo e Silva Defáveri et al., 2019) demonstrated that geopolymers synthesized with IOT as the main precursor, blended with glass wool residue, achieved compressive strengths exceeding 100 MPa and flexural strengths of 20 MPa, underscoring its efficacy as a precursor material. Beyond serving as a precursor, IOT can be processed to produce sodium silicate, a critical activator in geopolymer binders. (Figueiredo, Brandão, et al., 2021) has shown that silica extracted from IOT can be transformed into sodium silicate powder, which is then used in one-part geopolymer systems. This method reduces reliance on commercial activators, enhancing both cost-effectiveness and sustainability. In certain geopolymer formulations, IOT functions as a filler or aggregate, adjusting the material's physical properties. For instance, in the production of geopolymer bricks, IOT has been used to replace natural sand, contributing to the mechanical strength and durability of the final product. This role is particularly evident in studies combining IOT with other industrial wastes like slag sand and fly ash (Kumar et al., 2020).

Beside the abovementioned role for IOT in the production of geopolymer, IOT could play a chemical role in depolymerization and polymerization process in geopolymer. Geopolymerization begins with depolymerization, the process where aluminosilicate structures dissolve in an alkaline environment, releasing reactive silica and alumina species that subsequently polymerize into a geopolymer gel. The silica and alumina in IOT are essential for this initial step, providing the building blocks for the geopolymer network. However, the crystalline nature of some IOT minerals, such as quartz or hematite, can limit their reactivity. To address this, pretreatments like mechanical activation, calcination, or alkali roasting are often employed to enhance dissolution rates and improve geopolymerization efficiency(Xiaolong et al., 2021). Finialy, it could be emphasized that Iron content in IOT could play a notable role in the geopolymerization process beside depolymerizasion. recent studies suggest that iron can be incorporated into the geopolymer structure, potentially substituting for aluminum in tetrahedral coordination sites. This incorporation may influence the mechanical properties, durability, and chemical stability of the geopolymer. For example, research on one-part geopolymers synthesized with Brazilian IOT found that iron reacted within the geopolymer matrix, contributing to its structural integrity (Figueiredo, Silveira, et al., 2021).

3.1.Mechanical Performance

The analyzed studies utilized Iron Ore Tailings (IOT) as a raw material in geopolymer formulations, demonstrating significant variations in composition and mechanical properties. The result of XRF for studiesd article showed a similar trend in the composition of the IOT like the review research all over the word that previously showed in table 3. The IOT composition in these three study have shown in the Table 4.

Table 4. main composition of IOT in the studied articles.

	%							
State, Country	**SiO_2**	**Fe_2O_3**	**Al_2O_3**	**CaO**	**MgO**	**K_2O**	**Na_2O**	**Source**
Minas Gerais, Brazil	52.84	25.74	15.56	-	-	-	-	(Lorenzini et al., 2023)
Liaoning, China	87.65	5.72	0.81	1.87	1.81	0.08	0.20	(H. T. Wang et al., 2024)
Minas Gerais, Brazil	51.02	-	29.20	-	-	-	-	(Lameiras et al., 2023a)

Geopolymers synthesized from IOT and metakaolin typically exhibited strong mechanical properties, with compressive strengths ranging from approximately 31 to 38 MPa. Such values highlight the potential use of these geopolymers as sustainable alternatives to traditional Portland cement, given their competitive mechanical strengths and lower environmental impacts. The result of compressive strength for the chosen research alongside the optimum conditions and materials is shown in Table 5.

Table 5. The result of compressive strength and the optimum condition for chosen studies.

Source	Compressive Strength (MPa)	Optimum Conditions
(Lorenzini et al., 2023)	31.21	Metakaolin geopolymer, one-part synthesis method
(H. T. Wang et al., 2024)	35.4	Iron tailings-Fly Ash geopolymer, 30% tailings, liquid-solid ratio 0.5, cured at 60°C for 28 days
(Lameiras et al., 2023a)	37.9	Metakaolin geopolymer with tailings, Composition 1, calcined at 4 hours, tailings addition 50-60%

The geopolymerization process was critically influenced by several parameters, including curing temperature, reaction time, and material proportions. It was noted that increasing curing temperature generally enhanced geopolymer strength by facilitating the dissolution and polymerization of silica and alumina components. However, overly high temperatures or excessive alkali activation could negatively impact the microstructure, causing strength reductions. The best mechanical performance, characterized by optimal compressive strength, resulted from precise control over the reaction parameters, specifically the type of activator used, curing conditions, and the proportion of tailings incorporated.

In conclusion, these findings underscore the feasibility of incorporating industrial waste such as iron ore tailings into geopolymer matrices, providing a sustainable and environmentally beneficial method of waste valorization and contributing to the development of green building materials.

3.2.Environmental Performance

3.2.1 Wang-2024

The major sources of environmental impacts were sodium silicate and sodium hydroxide. Sodium silicate production has notable environmental impacts, particularly due to its energy-intensive manufacturing process. The synthesis typically involves melting silica sand with sodium carbonate at temperatures around 1400–1500 °C, leading to substantial energy consumption and associated CO_2 emissions (Delgado-Plana et al., 2024).

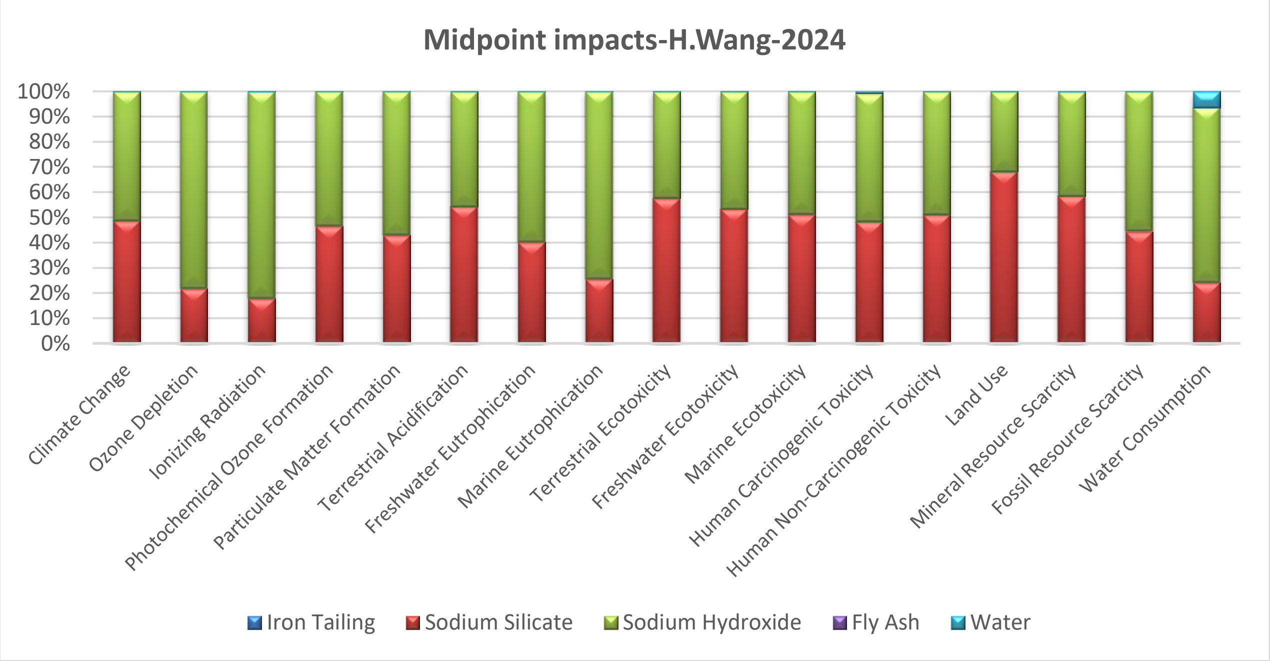

Figure 2. Midpoint Impacts of Wang-2024.

3.2.2 Lorenzini-2023

Potassium carbonate (K_2CO_3) production has notable environmental impacts which could be observed from figure 3, primarily due to its energy-intensive manufacturing process and the production of its precursor, potassium hydroxide (KOH). Life cycle assessments (LCAs) indicate that the electrolytic production of KOH significantly contributes to the global warming potential (GWP) associated with K_2CO_3 manufacturing. Additionally, the process consumes substantial amounts of electricity and natural gas, leading to emissions that contribute to ozone depletion and carcinogen production. While K_2CO_3 is non-toxic and does not bioaccumulate, its high alkalinity can increase the pH of waterways, potentially harming aquatic life. These findings underscore the importance of optimizing production methods and energy sources to mitigate the environmental footprint of K_2CO_3(Agriculture & Service, 2023).

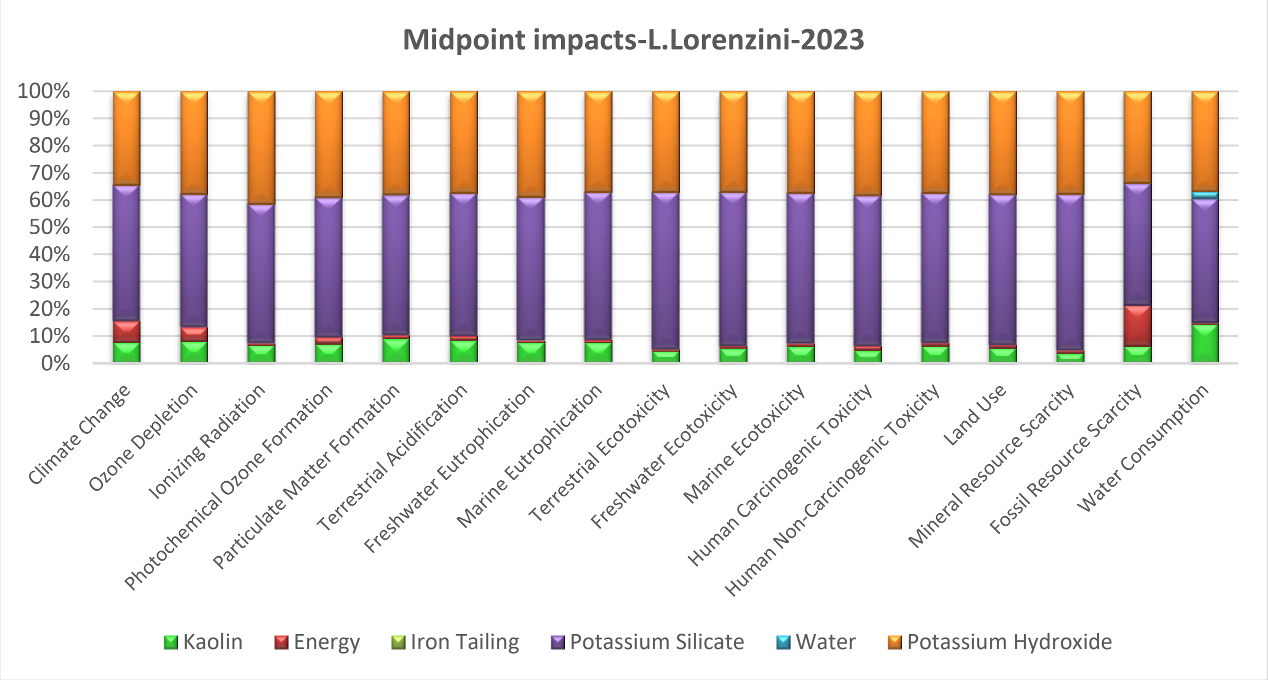

Figure 3. Midpoint Impacts of Lorenzini-2023.

3.2.3 F.Lameiras-2023

Similar to Wang-2024, and based on Figure 4, sodium silicate and sodium hydroxide are responsible for a significant part of environmental impacts; the third material that has a considerable contribution is metakaolin.

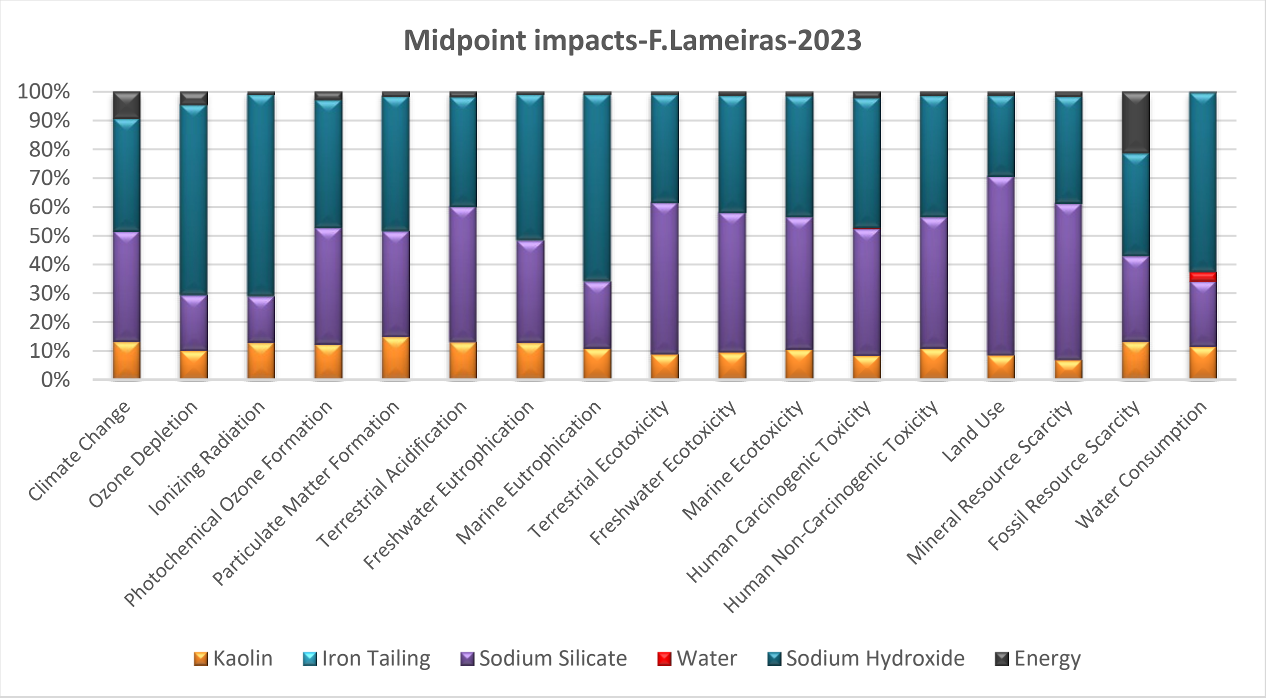

Figure 4. Midpoint Impacts of F.Lameiras-2023.

3.2.4 Comparison

One of the goals of performing LCA in this study was to give a clearer view of the environmental aspects of selected geopolymers. As it is illustrated in figure 5, L. L.Lorenzini had the most environmental impacts compared to F. F.Lameiras and Wang. The reason lies within the use of potassium silicate and potassium hydroxide. As for F.lameiras and Wang, it is clear that the greater amounts of sodium hydroxide and sodium silicate are the reason for the higher impacts. The results of the better environmental performance of sodium silicate than potassium silicate are similar to the work of Roux et al and the work of Martinez and Miller (Martínez & Miller, 2025).

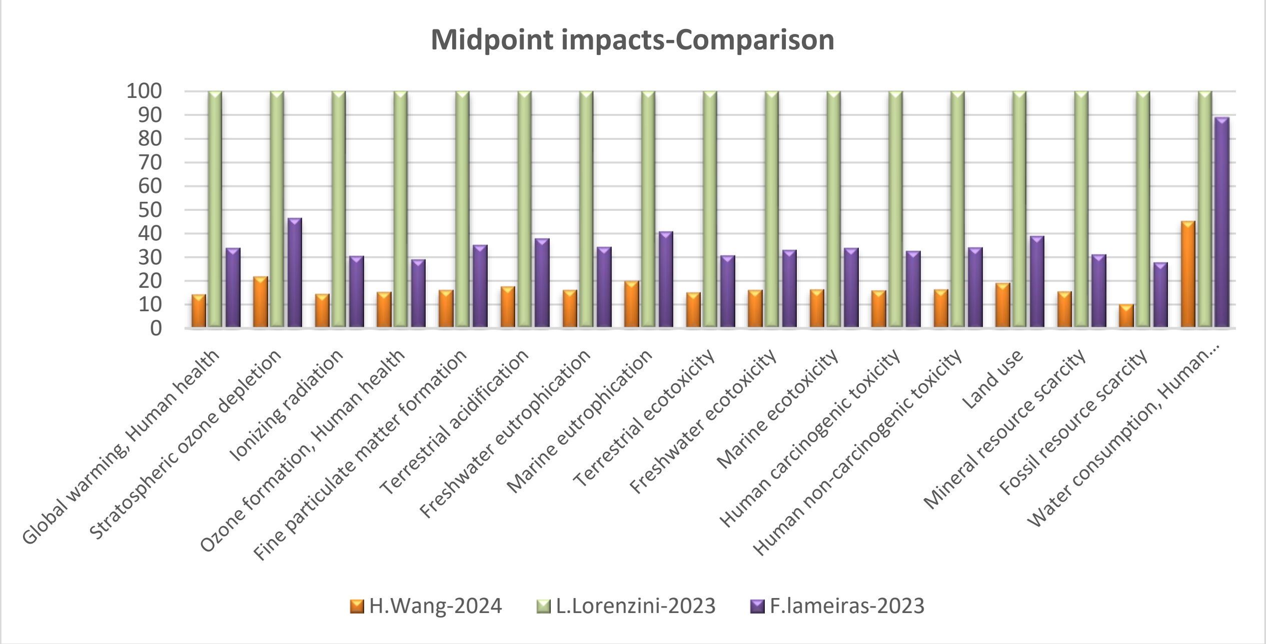

Figure 5. Midpoint Impacts Comparison.

4. Conclusions

This study demonstrates that iron ore tailings (IOT) can serve as a viable precursor in geopolymer formulations, paving the way for a dual benefit: enhanced mechanical performance and significant environmental advantages. The incorporation of IOT into geopolymer matrices not only capitalizes on a sustainable reuse of industrial waste but also contributes to reducing the environmental risks associated with tailing disposal. With compressive strengths consistently reaching the range of 30 to 40 MPa, in some cases approaching 50 MPa. The mechanical properties of these geopolymers affirm their potential as competitive alternatives to conventional cementitious materials.

A performed life cycle assessment has further highlightes the critical role of production of alkaline activators in the overall environmental performance of the geopolymer system. Among the activators analyzed, geopolymers employed sodium silicate and sodium hydroxide exhibit lower environmental impacts compared to their potassium based geopolymers. This insight not only underscores the importance of selecting appropriate activators but also suggests that further optimization of the mix design and curing parameters could further enhance sustainability.

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Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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