Materials Today Communications 35 (2023) 106082

Contents lists available at ScienceDirect

Materials Today Communications

journal homepage: www.elsevier.com/locate/mtcomm

Bibliometric trends of geopolymer research in Sub-Saharan Africa

Jabulani Matsimbe [a,b,c,*], Megersa Dinka [a], David Olukanni [d], Innocent Musonda [b]

[a] Department of Civil Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2006, South Africa
[b] Centre for Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2092, South Africa
[c] Department of Mining Engineering, Malawi University of Business and Applied Sciences, P/Bag 303, Chichiri, Blantyre3, Malawi
[d] Department of Civil Engineering, Covenant University, 10 Idiroko Road, Ota, Ogun State, Nigeria

ARTICLE INFO

Keywords:
Building materials
Concrete
Eco-friendly materials
Geopolymers
Green cement
Inorganic polymer

ABSTRACT

In recent years, geopolymers have been widely utilized as a potential alternative to ordinary Portland cement (OPC) to address issues related to CO_2 emissions and solid waste management. Unlike OPC, the mix design of geopolymers involves different parameters such as aluminosilicate precursors, alkaline activators, curing conditions, silica/alumina ratio, and liquid/binder ratio, to achieve satisfactory mechanical and structural properties. However, little is known about the trends and development of geopolymer research in Sub-Saharan Africa. Therefore, this study aims to examine the bibliometric status quo to understand the evolution and progress of geopolymer research in Sub-Saharan Africa (SSA) in the last 10 years. Scopus database and VOSviewer software were used for bibliometric data retrieval and network visualization. A total of 251 publications were retrieved from Scopus and showed steady growth from 2012 to 2022. It is found that the Construction and Building Materials journal (impact factor of 7.693 and h-index of 198) is the leading publication source having 41 publications and 1488 citations. The top journals in terms of average citation per publication are Ceramics International ($n = 53.22$), Construction and Building Materials ($n = 36.29$), and Cement and Concrete Composites ($n = 36.2$). Keywords with the highest occurrences are geopolymers, inorganic polymers, and compressive strength. Authors with the highest number of publications are Elie Kamseu ($n = 56$), Cyriaque Rodrigue Kaze ($n = 37$), and Herve Kouamo Tchakoute ($n = 34$) whilst those with the highest average citation per publication are Antoine Elimbi ($n = 68.5$), Patrick Lemougna ($n = 44.36$), and Uphie Chinje Melo ($n = 33.4$). The SSA countries with the highest number of publications are Cameroon ($n = 117$), Nigeria ($n = 58$), and South Africa ($n = 44$) contributing 45.45%, 22.57%, and 17.12% of the total publications, respectively. Compared to global publication trends, geopolymer research remains underexplored in SSA contributing less than 4.3% of worldwide geopolymer publications. Therefore, this bibliometric study provides insights into the scientific agenda and evolution status of geopolymer research in SSA to foster and identify future collaborative research areas and help address CO_2 emissions and solid waste management concerns in the built environment which is in line with circularity and sustainable development goals number 9, 11, 12, and 13.

1. Introduction

Ordinary Portland Cement (OPC) is the largest manufactured product on Earth by mass and is key for concrete production [1]. The global production of OPC is believed to reach 5 billion tonnes per annum in the next 30 years [2]. However, the manufacturing of OPC contributes about 8% to global anthropogenic CO_2 emissions [3,4] and is bound to increase as the global demand for OPC increases. This has sparked pressure from environmental regulatory authorities prompting the cement industry to minimize CO_2 emissions and adhere to sustainable development goals. An increase in urbanization and industrialization has led to an increase in construction projects and hence a significant demand for more sustainable cementitious materials. Furthermore, an escalation of industrial processes such as mining operations, agricultural processing, fertilizer manufacturing, and thermal production, has significantly increased the production of industrial by-products and/or waste. The disposal of generated industrial waste poses a risk to the environment and hence requires a circular economy approach to reuse it e.g., to

* Corresponding author at: Department of Civil Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2006, South Africa.

E-mail address: jmatsimbe@poly.ac.mw (J. Matsimbe).

https://doi.org/10.1016/j.mtcomm.2023.106082
Received 31 December 2022; Received in revised form 11 April 2023; Accepted 25 April 2023
Available online 27 April 2023

produce alternative eco-friendly cementitious materials for sustainable infrastructural development [5]. Among the various types of viable alternatives to OPC [6], geopolymer has gained wider research interest [7, 8] and has been extensively studied [9–11] due to its comparable physicomechanical properties [12], low CO_2 emission [13,14], reduced embodied energy [15], heat and fire resistance [16,17], resistance to aggressive environments [18,19], sustainability [20,21], and circularity [22,23]. Geopolymer is considered a third-generation cement after ordinary Portland cement and gypsum [24]. The term geopolymer was coined by a French scientist Professor Joseph Davidovits in 1978 [25,26] to represent an inorganic polymer product formed through the chemical reaction of aluminosilicate oxides (Al^{3+} in IV-fold coordination) with alkali hydroxide and silicate solutions yielding polymeric Si-O-Al bonds. When the aluminosilicate precursor is exposed to an alkaline solution, it undergoes dissolution, nucleation, oligomerization, polymerization and hardening to form the geopolymer network with a chemical formula of $Mn[-(SiO_2)z-AlO_2]n·wH_2O$ where n is the degree of polycondensation, z is 1, 2, 3 or 4 and M is a cation (K^+, Na^+, Ca^{2+}). The amorphous to semi-crystalline three-dimensional silico-aluminate structures are of the following types: Polysialate (-Si-O-Al-O) having Si:Al= 1, Polysialate-siloxo (-Si-O-Al-O-Si-O) having Si:Al= 2, and Polysialate-disiloxo (-Si-O-Al-O-Si-O-Si-O-) having Si:Al= 3 [25,26]. Different parameters such as precursor material properties, alkaline concentration, Si/Al ratio, and curing temperature have an impact on the speed and degree of geopolymerization [2]. To get an optimal mix design and a better geopolymer product with favourable engineering properties, it is important to include many factors affecting geopolymer behaviour during the mix design stage. Just like geopolymers, alkali-activated materials (AAM) have been greatly researched [27–31] and were developed by a Soviet Union scientist Professor Victor Glukhovsky in the 1950 s [10,32]. AAM represents any binder system derived by the reaction of an alkali metal source (solid or dissolved) such as alkali hydroxides or silicates, with an aluminosilicate precursor such as metallurgical slag, natural pozzolan, fly ash, or bottom ash [33]. When the aluminosilicate precursor is exposed to an alkaline solution, it undergoes the dissolution/breaking of the covalent (Si-O-Si, Al-O-Al, and Al-O-Si) bonds, speciation equilibrium, gelation, reorganization, polymerization, and hardening to form an amorphous to semi-crystalline three-dimensional silico-aluminate structure. The AAM phases of the hydration products (N-A-S-H or C-A-S-H gels) formed are characteristic of the presence of $R_2O-Al_2O_3-SiO_2-H_2O$, $R_2O-CaO-Al_2O_3-SiO_2-H_2O$, and $RO-SiO_2-H_2O$ where RO is Mg(Ca)O, and R_2O is $(Na, K)_2O$ [34]. The type of hydration product formed is dependent on the pH of the medium, Ca/Si, and Si/Al ratios. Despite subtle differences in the gel structure of AAM and geopolymers, the reaction mechanisms of the aluminosilicate precursor in the alkaline solution are similar. Since the production process, properties, and applications of AAM and geopolymers are very similar, the present study adopted the term 'geopolymers' for its bibliometric analysis.

Several authors have investigated the production and application of geopolymers in different environments. For instance, Kalombe et al. [35] studied the formulations and conditions of producing fly ash geopolymers without adding aggregates and Portland cement. The best geopolymer formulation with a compressive strength of 89.32 ± 7.1 MPa consisted of a water/fly ash ratio of 0.025, 16 M NaOH, $Na_2SiO_3/NaOH$ ratio of 2.5, 80 °C curing temperature, and a 28-day curing period. The roof tiles and paving bricks produced from their study met the SANS 1058:2012 and SANS 542:2012 specifications. The SANS 1058:2012 gives the performance requirements for concrete paving blocks comprising abrasion resistance of 15 g, water absorption of 6.5%, and splitting tensile strength of 2 MPa for Class 30/2.0 and 2.6 MPa for Class 40/2.6 blocks [36]. The SANS 542:2012 gives the performance requirements for roof tiles [37]. Naghizadeh and Ekolu [38] observed that the optimum compressive strength (60 MPa) for fly ash-based geopolymer mortars is found at a liquid/solid ratio of 0.5, 12 M NaOH, $Na_2SiO_3/NaOH$ ratio of 2.0, aggregate/binder ratio of 2.25, 80 °C curing temperature, and a 7-day curing period. Temuujin et al. [39] compared the compressive strength of alkali-activated Class C Mongolian fly ash and Class F South African fly ash varying the $Na_2SiO_3/NaOH$ ratios in the activator. It was found that the South African Class F fly ash gained 28 MPa and the Mongolian Class C fly ash gained 24 MPa both using a $Na_2SiO_3/NaOH$ of 50:50 wt%. Strength development in the Mongolian fly ash was attributed to the formation of C-S-H or C-A-S-H phases whilst strength for South African fly ash was attributed to condensation of the water glass followed by cross-linking of the polysiloxo chains into an aluminosilicate network. In another study, Tchadjié et al. [40] investigated the influence of incorporating activated bauxite on the mechanical properties and microstructure of volcanic ash geopolymer cement or binder composites. The optimum physical and mechanical properties comprising a compressive strength of 40.5 – 44.5 MPa, lowest water absorption of 6.7%, and least volume of permeable voids of 14.8% were found at 15 wt% bauxite content (with a fineness of 1000 – 1730 m^2/kg), SiO_2/Al_2O_3 ratio of 3.5, liquid activator/powder ratio of 0.6, water/powder ratio of 0.38, aggregate/powder ratio of 2.25, 12 M NaOH, and $Na_2SiO_3/NaOH$ ratio of 2.4. According to Ndlovu [41], a high percentage of silicon and aluminum in precursor materials e.g., fly ash, fosters the synthesis of zeolites and geopolymers. Guo et al. [42] utilized recycled glass powder as a partial replacement precursor of the metakaolin-based geopolymer to develop a sustainable geopolymer product. The glass powder substituted 0%, 5%, 10%, and 20% of the metakaolin in the geopolymer binder. The added glass powder increased the Si/Al ratio of the binder phase, increased the workability due to the relatively smooth surface of the glass particles and the low surface area which reduced the water demand to wet the solid precursor, and prolonged the setting time due to the relatively low reactivity of the glass powder which reduced the polycondensation rate of the mixtures during the reaction. The four-membered ring structures increased in the synthesized geopolymer with up to 10% glass powder substitution producing a denser binder structure. The elastic modulus of the formed gel increased with 10% and 20% glass powder substitutions whilst the highest compressive strength was observed at 5% glass powder substitution. However, the compressive strength of the metakaolin-based geopolymer decreased beyond 10% glass powder substitution due to the relatively low reactivity of glass powder which provided weak regions for micro-crack formation. Similar findings on the utilization of waste glass powder for geopolymer production were observed by Adesina et al. [30] and El-Naggar et al. [43]. Studies by Ogwang et al. [44] and Buyondo et al. [45] inferred that the mechanical properties of rice husk ash-metakaolin-based geopolymer activated with Na_2SiO_3 and NaOH improved with an increase in curing time. Similarly, Falayi [46, 47] observed that the compressive strength of geopolymers is directly proportional to curing temperature and time. In ref. [46], the increase in compressive strength was statistically significant up to 21 days and 28 days of ambient curing for the aluminate-activated and silicate-activated FeCr slag geopolymers, respectively. In ref. [47], the increase in compressive strength of basic oxygen furnace slag-gold mine tailings geopolymers under accelerated curing temperature (50–90 °C) was attributed to an increase in molecular kinetic energy which increased the degree of reaction in the aluminosilicate network. For basic oxygen furnace slag-gold mine tailings geopolymers, 6-hour curing at 50 °C followed by 21 days of ambient curing was considered the optimum giving an unconfined compressive strength of 14.73 MPa whilst, for fly ash-gold mine tailings geopolymers, 6-hour curing at 90 °C followed by 21 days ambient curing was considered the optimum giving an unconfined compressive strength of 6.77 MPa. Sithole et al. [48] evaluated the potential use of basic oxygen furnace slag-fly ash (BOFS-FA) geopolymer in removing metals and sulphates and neutralizing acid mine drainage (AMD). Hydrogen Peroxide (H_2O_2) was used as a blowing agent to increase the porosity of the BOFS-FA geopolymer at four different percentages (1.5%, 1%, 0.5%, and 0%). The four different geopolymers with distinct porosities were employed in different columns. It was found that over 99% removal efficiency of metals and sulphates was achieved in the first 60 days of column studies. The dissolution of $Ca(OH)_2$ was the main constituent responsible for the removal of acidity in AMD. In another study, Roopchund et al. [49] determined the effect of sawdust-based cellulose nanocrystals on the mechanical properties of fly ash geopolymers. It was found that low cellulose nanocrystals concentrations (less than 0.5%) yielded higher compressive strength of geopolymers due to its adhesive property which increased the bonding between particles. However, beyond the 0.5% inclusion of cellulose nanocrystals, the compressive strength of the geopolymer decreased due to the agglomeration of the cellulose nanocrystals leading to pores, voids, and air entrapment in the composite material. Similar findings were observed by Rahmawati et al. [50] and Cao et al. [51]. According to Dludlu et al. [52], geopolymers used in high-temperature applications are affected by the particle size influencing aluminosilicate reactivity, glass content influencing the amount of reactive material, Si:Al ratio in the glass phase controlling mechanical strength and thermal resistance, iron content influencing thermal stability, and calcium content influencing setting time.

Traditional review techniques are shown to be inadequate and biased in giving an ordered and systematic connection between distinct areas of the literature [53,54]. The bibliometric method depicts the knowledge trend of distinct research areas, provides information on the most active authors/countries, and gives insights into the past and future projections of research fields worldwide [11, 55–57]. Not only has the bibliometric method been used to analyze research trends in geopolymers [11,54,55,57] but it has also been used to analyze research trends in concrete [58], nanomaterials [59], zero-energy buildings [60], circular economy [61], sustainable construction [62], phosphogypsum valorization [63], bioeconomy [64], medicine [65], cloud computing [66] and wastewater treatment [67]. This shows the diversity of the bibliometric method worldwide and validates its applicability to the present study. A few authors have conducted bibliometric analyses of geopolymers in distinct areas. For instance, Alkadhim et al. [54] conducted a scientometric analysis of fiber-reinforced geopolymers using the Scopus database and VOSviewer software. They found that the most used keywords are inorganic polymers, geopolymers, reinforcement, geopolymer, and compressive strength. Furthermore, it was found that research on fiber-reinforced geopolymers is focused on improving mechanical performance and durability to reduce brittleness and cracking. The leading countries in terms of publications were Australia, China, India, and the United States. The graphical illustration and quantitative contribution of authors, journals, and countries can support the development of joint ventures and the dissemination of innovative ideas. Yang et al. [55] conducted a bibliometric analysis on geopolymer composites and observed that there are gaps between research and industrial acceptance of geopolymers due to the need for precise mix design formulation and curing, technological problems associated with forms of usage, missing design standards, regulatory and product confidence barriers, and supply chain constraints. However, geopolymer technology offers an eco-friendly alternative to ordinary Portland cement and addresses the issue of environmental pollution [10,15,24,68,69]. Tian et al. [56] conducted a bibliometric analysis of fly ash-based geopolymer and observed that the development of fly ash-based geopolymer can be divided into 3 stages: the replacement of ordinary Portland cement, the development of multifunctional materials, and the reduction of environmental impact by solid waste conversion. It was further found that the leading countries in terms of publications were China, Australia, India, and the United States contributing 16.45% (1st place), 10.14% (2nd place), 7.67% (3rd place), and 6.68% (4th place) of the 4352 total publications, respectively. This finding agrees with Matsimbe et al. [11] who observed that research in geopolymers is dominated by countries in Asia, Australia, America, and Europe. They further showed that Northern Africa dominates in geopolymer research in the whole of Africa and therefore recommended scaling up geopolymer research in Sub-Saharan Africa. However, they did not show the trends and patterns of geopolymer research in Sub-Saharan Africa (SSA). There is no available literature that has addressed this gap hence the motivation for the present study. Sub-Saharan Africa is now prioritizing investment in scientific research and innovation to boost its socio-economic development and transition to knowledge-driven economies. For example, in South Africa, the gross domestic expenditure on research and development (GERD) for 2020/21 was R33.541 billion where the Government, business community, and foreign institutions contributed 56.3%, 26.9%, and 13.3% of GERD, respectively [70]. According to the United Nations [71], the population of SSA stands at 1183,248,018 compared to Northern Africa's population at 246,232,518. By 2060, the population of SSA is projected to reach 2.7 billion [72]. Compared to Northern Africa and any other region worldwide, the SSA is the least developed region [73,74] embattled with severe poverty, housing shortage, solid waste management, and increased demand for urbanization and industrialization requiring more cementitious materials for construction projects. Hence, there's a need to investigate the human capital development, promotion, and support of geopolymer research (eco-friendly material) in SSA as an alternative to OPC (eco-hostile material) to help address CO_2 emissions and solid waste management (in terms of scale) and to competitively level up the geopolymer knowledge base with Asia, Australia, America, Europe, and Northern Africa whilst addressing sustainable development goals number 9, 11, 12, and 13. The awareness level of geopolymers in SSA for use in the built environment remains relatively low due to limited research and development output which might hinder the advancement of new research, academic networks, and industry adoption. The key question to be addressed is whether Sub-Saharan Africa has the expertise and capacity to promote, collaborate, and strengthen scientific research in geopolymers. Therefore, this study seeks to fill the research gap by conducting a bibliometric analysis of the geopolymer research trends and progress in SSA and establishing empirical benchmarks for future investigations.

2. Methodology

This study applied the bibliometric method to statistically and quantitatively analyze the different aspects of the bibliographic data from 2012 to 2022. The most common scientific databases are Scopus, Web of Science, and Google Scholar [75]. However, the Scopus database is chosen to retrieve bibliographic data for the present study because it is considered the world's largest academic citation and abstract database [76,77] and covers a comprehensive range of subjects and contents [60,78,79]. VOSviewer software, designed by Nees and Waltman [80,81], was used for bibliographic data visualization and network mapping based on citation, co-citation, co-occurrence, and co-authorship relationships. Table 1 shows the inclusion criteria used for data retrieval in Scopus as of 9th November 2022. This study focused on the annual publication trend, keyword co-occurrence, and the contribution of publication sources, authors, top-cited publications, and countries.

With reference to Table 1, the data extraction process is explained as follows. Firstly, the language used is English only and the search query comprised the keyword "geopolymer" on the topic (Title, Abstract, Keywords). Secondly, the search was limited to peer-reviewed scientific journal articles and reviews in "Engineering, Material Science, and Environmental Science" published between 2012 and 2022. Thirdly, the retrieved results were filtered to include Sub-Saharan African countries

Table 1
The inclusion criteria for data retrieval in Scopus.

Option	Inclusion Criteria
Language	English
Publication date	2012–2022
Subject area	Engineering, Material Science, Environmental Science
Source type	Journal
Document type	Article, Review
Country/Territory	Sub-Saharan African countries

only. The inclusion of Sub-Saharan African countries differentiated the present study from previous studies [11, 55–57] to address the existing gap in the development status and trend of geopolymer research in SSA. Fourthly, the authors went through all the abstracts to ascertain the relevance of the retrieved articles to the present study as well as to remove duplicates if any. Finally, the remaining bibliographic data was exported to VOSviewer version 1.6.18 in CSV format to construct and visualize the bibliometric networks based on citation, co-citation, co-occurrence, and co-authorship relationships.

3. Results and Discussion

3.1. Annual publication trend

Based on the Scopus database and the inclusion criteria in Table 1, this study retrieved 251 publications on geopolymers in SSA for the period 2012–2022. According to [67], the number of yearly publications can reflect the development trend in that specific field. It can either showcase a growing interest in a research area or no focus at all. Fig. 1(a) shows the yearly publication trend of geopolymer research in SSA from 2012–2022. The research in geopolymer has had a steady growth starting with 2 publications in 2012–73 publications by 9th November 2022, giving an annual growth rate of 43.29%. Cumulatively, the trend increased from an initial stage of 2 publications to an upward gradual trend reaching 251 publications. Fig. 1(b) shows that the exponential regression of publications was significant with an R-squared (R^2) value of 0.9901 denoting a positive trend in geopolymer research in Sub-Saharan Africa. Compared to global publication trends, geopolymer research remains underexplored in SSA contributing less than 4.3% of total worldwide geopolymer publications. This agrees with Matsimbe et al. [11] and Olonade [82] who observed that geopolymer research is still emerging in most African countries. China, India, Australia, and the USA rank first, second, third, and fourth in global geopolymer development contributing 16.1%, 12.75%, 9.33%, and 6.46% to worldwide geopolymer publications, respectively [11]. This clearly shows a low publication trend of geopolymer research in SSA compared to other continents and requires greater support to expand the research and development of geopolymers.

Fig. 1 shows that there was a decline in publications in 2014 and then a gradual rise in publications from 2015. The increase in geopolymer research publications can be attributed to the growing interest in the circular economy approach, solid waste management, and the United Nations sustainable development goals (SDG) number 9, 11, 12, and 13 adopted in 2015 [83]. This finding agrees with Det Udomsap [62] and Mhlanga et al. [61] who observed that sustainable construction and circular economy is a game changer within the construction industry as it addresses challenges in waste management, pollution, climate change, and material extraction. Furthermore, the United Nations Habitat Report 2011 [84] emphasizes the need to produce cost-effective and eco-friendly building materials in Africa. Therefore, the publication trend from the present study infers that research in geopolymer will continue to grow exponentially due to policies implemented to improve the built environment locally and globally. However, the research output in Sub-Saharan Africa is still marginal compared to Asia, Australia, America, and Europe [11] hence the need to scale up geopolymer research and establish development centres in Sub-Saharan Africa which is regarded as an emerging region.

3.2. The contribution of publication sources

This study also examined the leading journals for geopolymer publications in Sub-Saharan Africa. It is imperative to get a perspective on the contribution of publication sources to the knowledge dissemination of geopolymer research. The metrics used to measure the importance of a journal were the Hirsch index (H-index) and journal impact factor (JIF). Authors [11,67,85] used a similar technique of H-index and JIF to check the influence, authority, and relative quantitative characteristics of a journal within its field. Table 2 ranks the top publication sources for geopolymer research in SSA. Construction and Building Materials (n = 41), Silicon (n = 15), Case Studies in Construction Materials (11), and Materials (n = 10) are the top four publication sources for geopolymer research in terms of the number of publications. Furthermore, Construction and Building Materials (n = 1488), Ceramics International (n = 749), Case Studies in Construction Materials (n = 287), and Journal of Building Engineering (n = 266) have the highest total number of citations. However, Ceramics International has the highest average number of citations (n = 53.22) followed by Construction and Building Materials (n = 36.29) and Cement and Concrete Composites (n = 36.2). Interestingly, most journals with an H-index greater than 100 and a JIF greater than 3, have a total number of citations greater than 100 compared to the rest of the journals. The only exception is Case Studies in Construction Materials with an H-index of 36 and Journal of Building Engineering with an H-index of 54 which also have a total number of citations greater than 100. It can be inferred from Table 2 that the total and average number of citations is not always proportional to the number of publications within the field.

Fig. 2 shows the network visualization of the top publication sources for geopolymer research. It depicts that there are 3 clusters/groups of

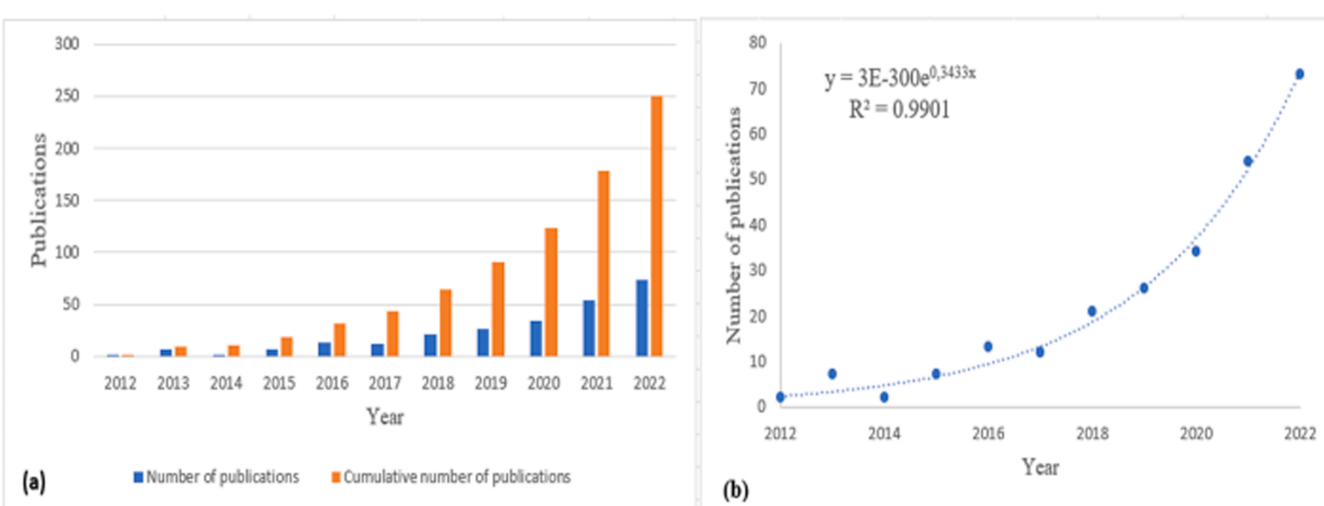

Fig. 1. (a) Yearly publication trend (b) Exponential regression of publications.

Table 2
Top 10 publication sources.

S/N	Source	Number of Publications	Total Citations	Average Citation	JIF	H-index
1	Construction and Building Materials	41	1488	36.29	7.693	198
2	Silicon	15	75	5	2.941	34
3	Case Studies in Construction Materials	11	287	26.09	4.934	36
4	Materials	10	101	10.1	3.748	128
5	Ceramics International	9	479	53.22	5.532	126
6	Materials Chemistry and Physics	9	213	23.67	4.778	162
7	Journal of Building Engineering	9	266	29.56	7.144	54
8	SN Applied Sciences	7	69	9.85	2.679	28
9	Advances in Materials Science and Engineering	6	4	0.67	2.098	50
10	Cement and Concrete Composites	5	181	36.2	9.93	174

journals interrelated and linked in citation. The journals in Cluster 1 (green colour) comprise Construction and building materials, Case studies in construction materials, Materials, and Advances in materials science and engineering. The journals in Cluster 2 (red colour) comprise Silicon, Journal of building engineering, Materials chemistry and physics, and Cleaner materials. The journals in Cluster 3 (blue colour) comprise Cement and concrete composites, Ceramics international, and Sn applied sciences. The size of the circle indicates the document count of that journal i.e., the bigger the circle size the higher the number of published documents. Construction and Building Materials journal has the biggest circle size implying its relevance and impact in disseminating geopolymer research. This finding agrees with authors [55,57], and [11] who observed that Construction and Building Materials is a leading journal on geopolymer research publications. Furthermore, the closeness of journals within/between Clusters indicates the connection and interrelationship between the journals. For example, Construction and Building Materials has a closer relationship with Silicon than Ceramics International.

3.3. Keyword co-occurrence

Keyword co-occurrence analysis is carried out to examine the core areas and hotspots of the research domain. Table 3 shows the most occurring keywords in geopolymer research conducted in SSA. The top most used keywords comprise Geopolymers (n = 189), Inorganic polymers (n = 186), and Compressive strength (n = 134). The popularity of these keywords can be attributed to the increased need to further understand the link between the chemical, microstructure, and mechanical behaviour of geopolymers. This finding agrees with authors [11,54], and [57] who also found that inorganic polymers, geopolymers, and compressive strength are the commonly occurring keywords in geopolymer publications worldwide.

Fig. 3 shows the visualization of the leading keywords in geopolymer research domains. There are three clusters/groups identified in the network visualization comprising Cluster 1 (red colour), Cluster 2 (green

Table 3
List of commonly used keywords in geopolymer publications.

S/N	Keyword	Occurrence
1	Geopolymers	189
2	Inorganic polymers	186
3	Compressive strength	134
4	Sodium hydroxide	61
5	Geopolymer concrete	60
6	Fly ash	57
7	Silicates	54

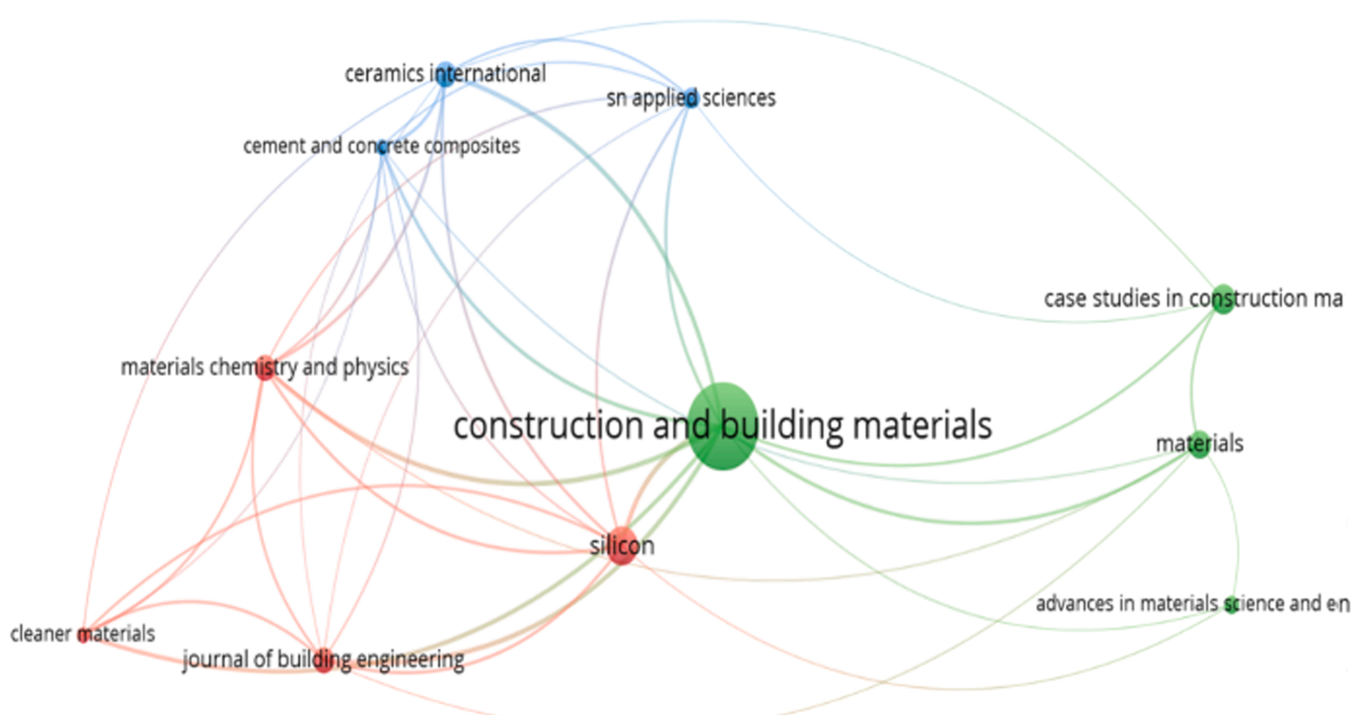

Fig. 2. Network visualization of top publication sources.

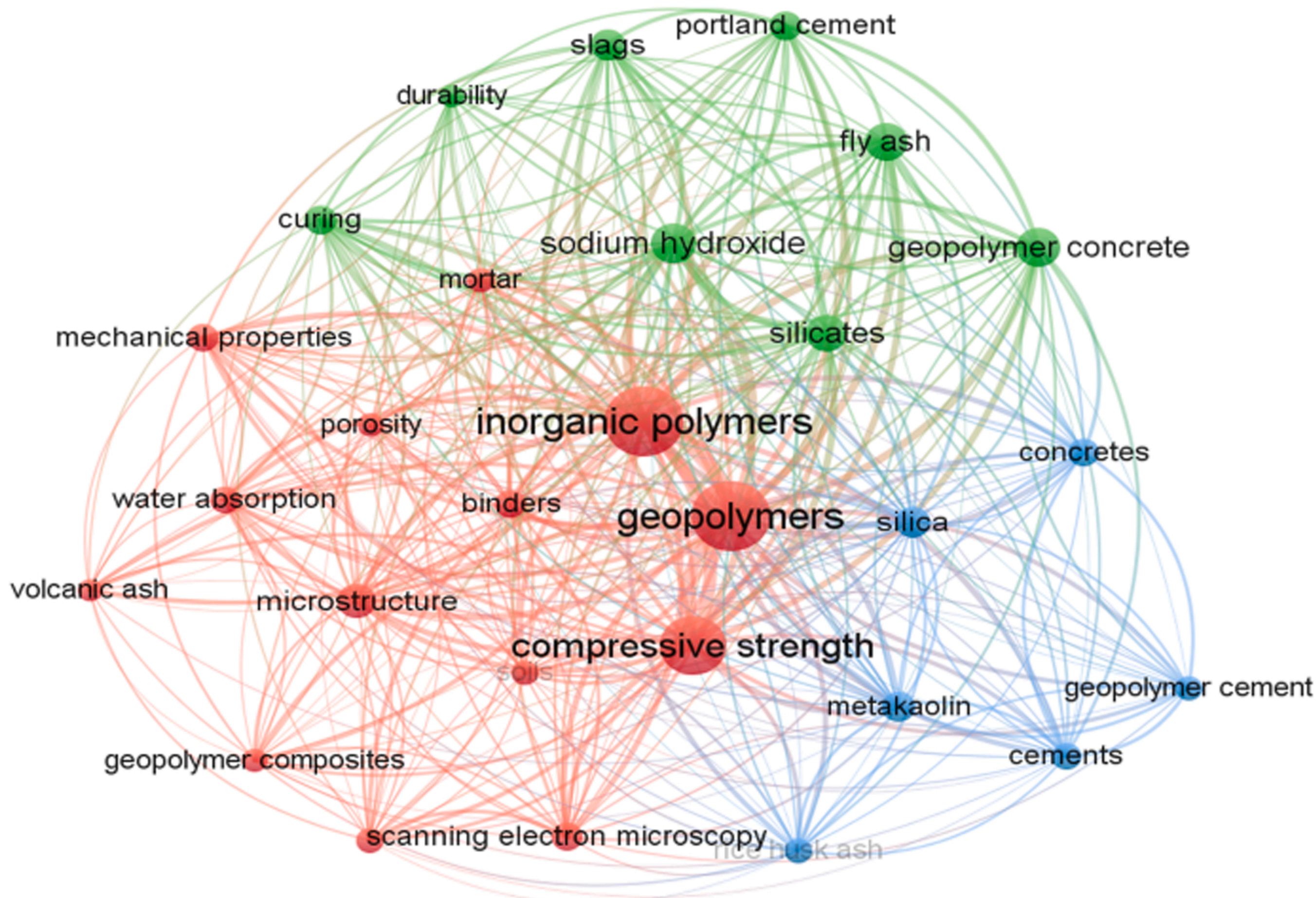

Fig. 3. Network visualization of keyword co-occurrence.

colour), and Cluster 3 (blue colour). The circles with larger sizes e.g., Geopolymers and Inorganic polymers, imply prominent keywords in geopolymer research compared to the other keywords with smaller circles. Compressive strength is the most important mechanical property in construction and building since the concrete material must sustain maximum structural load before failure. The compressive strength of geopolymers is mostly affected by the type of aluminosilicate precursor, type and concentration of alkaline activator, liquid/binder ratio, silica/alumina ratio, and curing condition. Also of importance are the natural precursor materials keywords e.g., 'metakaolin' and 'soils', which are used standalone or alongside industrial waste materials such as fly ash, slags, and rice husk ash, to produce geopolymers with improved mechanical properties [55]. The presence of the keyword 'soils' can imply the usage of lateritic soils to produce geopolymers [86–88] and the usage of geopolymers in soil stabilization [89–91]. The major challenge with the usage of metakaolin or lateritic soils in geopolymer production is that their manufacture requires thermal activation (calcination) at temperatures ranging from 500° to 800°C [55,86] thereby adding to the energy demand, CO_2 emissions, and depletion of natural resources.

3.4. Analysis of leading authors

Recognizing the leading authors is a good performance indicator because progress in geopolymer research in SSA is dependent on authors conducting scientific research and publishing the results to advance knowledge and understanding. The authors listed in Table 4 have made

Table 4
Leading authors based on publication and citation.

S/N	Author	Affiliation	Publications	Total Citations	Average Citation	Total Link Strength
1	Elie Kamseu	Local Materials Promotion Authority/MIPROMALO, Cameroon	56	1249	22.30	1229
2	Cyriaque Rodrigue Kaze	University of Yaounde I; Local Materials Promotion Authority/MIPROMALO, Cameroon	37	732	19.78	1232
3	Herve Kouamo Tchakoute	University of Yaounde I, Cameroon	34	1073	31.56	1051
4	Uphie Chinje Melo	University of Yaounde I; Local Materials Promotion Authority/MIPROMALO, Cameroon	25	835	33.4	800
5	Jean Noël Yankwa Djobo	Local Materials Promotion Authority/MIPROMALO, Cameroon	18	550	30.56	414
6	Achile Nana	University of Dschang, Cameroon	13	223	17.15	487
7	Antoine Elimbi	University of Yaounde I, Cameroon	12	822	68.5	201
8	Patrick Lemougna	University of Ngaoundere, Cameroon	11	488	44.36	187

the most outstanding contribution to the literature on geopolymers. Elie Kamseu affiliated with the Local Materials Promotion Authority has the highest number of publications (n = 56) followed by Cyriaque Rodrigue Kaze with 37 publications, and Herve Kouamo Tchakoute with 34 publications, both from the University of Yaounde I in Cameroon. In terms of the total number of citations, the top three authors are Elie Kamseu (n = 1249), Herve Kouamo Tchakoute (n = 1073), and Uphie Chinje Melo (n = 835). Interestingly, Antoine Elimbi has the highest average citation of 68.5 followed by Patrick Lemougna with an average citation of 44.36. Furthermore, Cyriaque Rodrigue Kaze has the highest total link strength of 1232 indicating a stronger influence and connection with other authors both at local and international levels. All the leading authors shown in Table 4 are from Cameroon implying that the country has made the most significant contribution to geopolymer literature in SSA. This positive trend in Cameroon can be attributed to the promotion of using sustainable local materials in construction and the dissemination of building materials research by the Local Materials Promotion Authority (MIPROMALO) through support from the European Union and the Ministry of Scientific Research and Innovation. This observation agrees with Lemougna et al. [92] who acknowledged contributions by the Cameroonian government in promoting the usage of local materials for construction. Furthermore, there is strong collaboration and joint ventures between researchers from MIPROMALO and local universities such as the University of Yaounde I, University of Ngaoundere, University of Douala, University of Dschang, and University of Johannesburg – South Africa, as well as strong links with international universities such as the University of Modena and Reggio Emilia – Italy, Vrije Universiteit Brussel - Belgium, and Guangxi University – China. This strong collaborative trend shows significant promotion and dissemination of geopolymer research not only in SSA but also in other continents. Matsimbe et al. [11] found that the leading geopolymer authors in terms of publications worldwide are Jay Sanjayan - Swinburne University of Technology, Prinya Chindaprasirt - Khon Kaen University, and Mohd Mustafa Al Bakri Abdullah - Universiti Malaysia Perlis whilst those leading in terms of average citations are John Provis – University of Sheffield, Van Chai Sata – Khon Kaen University, and Zuhua Zhang - Hunan University. Zakka et al. [57] found that John Provis, Prinya Chindaprasirt, Mohd Mustafa Al Bakri Abdullah, Jannie van Deventer, and Jay Sanjayan are the most influential authors in terms of citations and publications in geopolymer concrete research. However, Tian et al. [59] found that Prinya Chindaprasirt, Ali Nazari, Mohd Mustafa Al Bakri Abdullah, Zuhua Zhang, John Provis, and Jay Sanjayan are the leading authors in terms of publication in the field of fly ash-based geopolymer. The foregoing shows that authors in SSA and/or Africa, in general, are yet to make a worldwide leading visibility in terms of publication and citation in the field of geopolymers.

Fig. 4 shows three clusters of geopolymer researchers comprising Cluster 1 (Kamseu e., Melo u.c, Kaze c.r., Nana a., Nemaleu j.g.d., Adesina a.), Cluster 2 (Tome S., Djobo j.n.y., Alomayri t., Lemougna p.n., Elimbi a., Ekolu S.), and Cluster 3 (Tchakoute h.k., Nanseu-njiki c.p.). There is a strong link between the leading authors implying significant collaboration in the field of geopolymers. Some authors are believed to work and/or share a similar research lab [93,94]. The leading authors have shown a trend of collaborating with their regional SSA partners. For example, Elie Kamseu, Cyriaque Rodrigue Kaze, and Uphie Chinje Melo have collaborated with Stephen Ekolu - Nelson Mandela

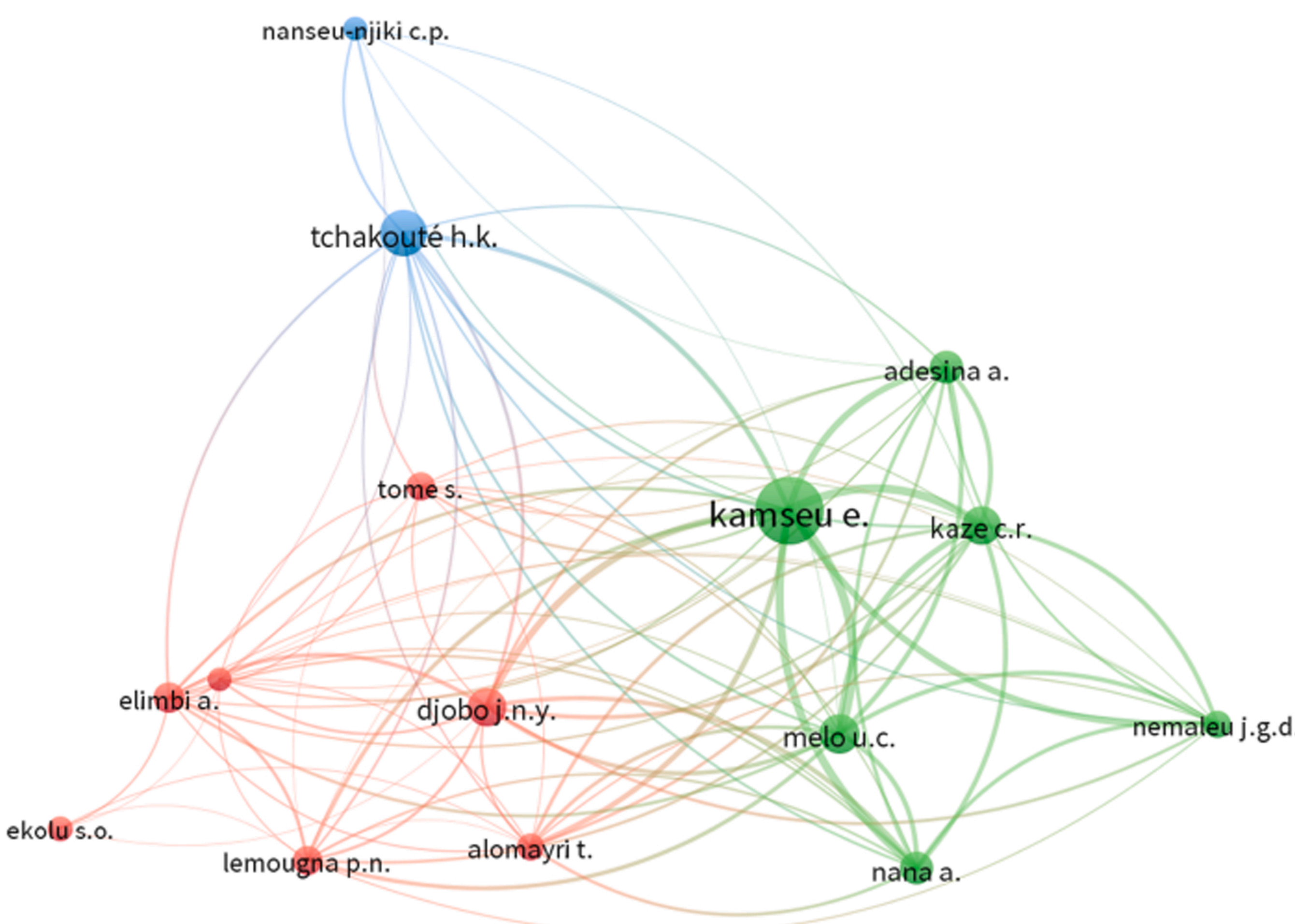

Fig. 4. Network visualization of leading authors.

University, Leonel Tchadjie - University of Johannesburg, and Abdolhossein Naghizadeh - University of Free State [40,86]. Notably, the geopolymer research areas currently studied by the leading authors comprise lateritic soils [86,95,96], volcanic ash [40], metakaolin-meta-halloysite blends [97], porous geopolymers [98,99], room temperature curing and user-friendly activators [100].

3.5. The contribution of most cited publications

Table 5 shows the most cited publications. The most cited study is "Geopolymer binders from metakaolin using sodium waterglass from waste glass and rice husk ash as alternative activators: A comparative study" [101] which received 143 citations. The second-ranked study is "The effect of adding alumina-oxide to metakaolin and volcanic ash on geopolymer products: A comparative study" [102] which received 126 citations. The third-ranked study "Utilization of volcanic ashes for the production of geopolymers cured at ambient temperature" [103] received 110 citations. It is followed by the studies "Potential of using granite waste as raw material for geopolymer synthesis" [104] which received 107 citations; "A critical review on application of alkali-activated slag as a sustainable composite binder" [105] which received 107 citations, and "Substitution of sodium silicate with rice husk ash-NaOH solution in metakaolin based geopolymer cement concerning reduction in global warming" [106] which received 101 citations. An examination of the most cited articles shows that the studies are cited globally by different authors showing the impact of geopolymer publications from SSA at local and international levels. Most of the authors citing the most-cited geopolymer articles are interested in understanding the physico-chemical properties of different natural and inorganic industrial waste materials, binder design, promoting ambient curing, developing user-friendly activators, advancing environmental-friendly industrial applications, durability, and life cycle assessments.

Fig. 5 shows how the most cited publications are interlinked with other publications. The size of the circle is proportional to the impact made by the publication. For example, it can be observed that the publication by Tchakouté et al. [101] has the biggest circle size and therefore has made the most significant influence in the field of geopolymers compared to the other publications.

3.6. Countries' contribution

Table 6 shows that Cameroon has the highest number of publications (n = 117) and citations (n = 3098) followed by Nigeria with 58 publications and 869 citations. Ranked third is South Africa with 44 publications and 391 citations. The authors checked if there is a link between a country's nominal GDP and the number of publications. A similar check was done by [11] who observed that countries with higher nominal GDP usually had shown higher interest in geopolymer research. In terms of nominal GDP rank in SSA, Nigeria (=31) is leading followed by South Africa (=39). However, Cameroon (n = 95) ranks 6th in terms of nominal GPD but it is leading in terms of geopolymer publications and citations. Furthermore, Cameroon has the highest number of citations and contributes 45.53% of the total publications. This implies that Cameroon is greatly invested in geopolymer research and fostering collaborations worldwide. Therefore, it can be inferred that a country's nominal GDP is not always connected to its geopolymer research output. It is worth noting that Malawi which is ranked 7th in terms of nominal GDP (=149) has shown interest in geopolymer research and has contributed 4 publications and 20 citations. Despite the lower rankings in nominal GDP for SSA countries compared to countries in Europe, America, Asia, and Australia, it shows that SSA Governments are gradually increasing the support and funding for the research and development of geopolymers.

Table 5
Publications with a minimum of 100 citations.

S/N	Publication	Total Citations
1	Tchakouté et al.[101]	143
2	Tchakoute et al.[102]	126
3	Tchakoute et al.[103]	110
4	Tchadjié et al.[104]	107
5	Awoyera & Adesina[105]	106
6	Kamseu et al.[106]	101

Fig. 6 shows that there are two major clusters comprising Cluster 1 (Cameroon, Belgium, Canada, France, Italy, Saudi Arabia) and Cluster 2 (Nigeria, South Africa, Ethiopia, Kenya, Uganda, Malawi, Germany, Malaysia, Trinidad & Tobago, Turkey, United States, Vietnam). The network shows that authors from Cameroon have the highest production of geopolymer research and are collaborating with different authors worldwide [21,88,93,104].

Most African academics/researchers conduct their postgraduate and postdoctoral studies at local and international universities. This exposes them to advanced research labs in waste materials valorization and geopolymer development thereby increasing the presence and impact of African researchers at the global level. The promotion of sustainable development goals, capacity-building training exchanges, international joint ventures, collaborations, and increased funding in research and development have greatly contributed to the growth of geopolymer research in SSA. This assertion agrees with Kahn [107] who attributed the growth in scientific research outputs in South Africa to collaboration with international authors and an increase in the Department of Education publication subsidy. According to OECD [108], international organizations must coordinate their data collection and research activities to mutualize the benefits of evidence sharing.

4. Future research trends

The bibliometric analysis revealed 9 interlinked intellectual and evolutionary research themes being explored and bound to continue in the next decade or so since the geopolymer technology is still evolving to gain widespread industrial use just like ordinary Portland cement which has been researched and used for over 200 years. The identified themes in the present study comprise 'user-friendly activators', 'just-add-water geopolymer cement', 'ambient curing', 'aluminosilicate precursors', 'mechanical properties', 'durability', 'microstructure', 'mix design', 'reinforcement', and 'industrial applications'. The primary production of conventional activators such as sodium silicate and sodium hydroxide add to the greenhouse gas emissions and embodied energy, is expensive, and caustic [24,101,109] hence requires efforts to develop activators and/or reagents which are greener, low cost, and user-friendly. The research on just-add-water geopolymer cement, like for OPC, has gained momentum as the powdered alkaline activator is premixed with the aluminosilicate source making the production process less caustic. It can be prepared just like ordinary Portland cement paste, mortar, and concrete by just adding water to the dry mix [110–113]. Therefore, just-add-water geopolymer cement is a hot topic requiring further research to understand the reaction processes, microstructure, and early-age properties.

The geopolymerization process requires heat curing at temperatures ranging from 60 °C to 120 °C to facilitate setting and strength gain which poses a challenge to cast-in-situ applications. Therefore, further research in ambient curing of geopolymers is needed to expand the application of geopolymers to cast-in-situ situations with lower energy requirements, good workability, and faster setting time, hardening, and strength-gain just like ordinary Portland cement [113–116]. The research on various natural and industrial waste aluminosilicate precursors [82,86,96,112, 117–119] requires further attention to understand the binder structure, reaction processes, and early age engineering properties under different deteriorating environments. Mechanical properties such as compressive, tensile, and shear strength provide a

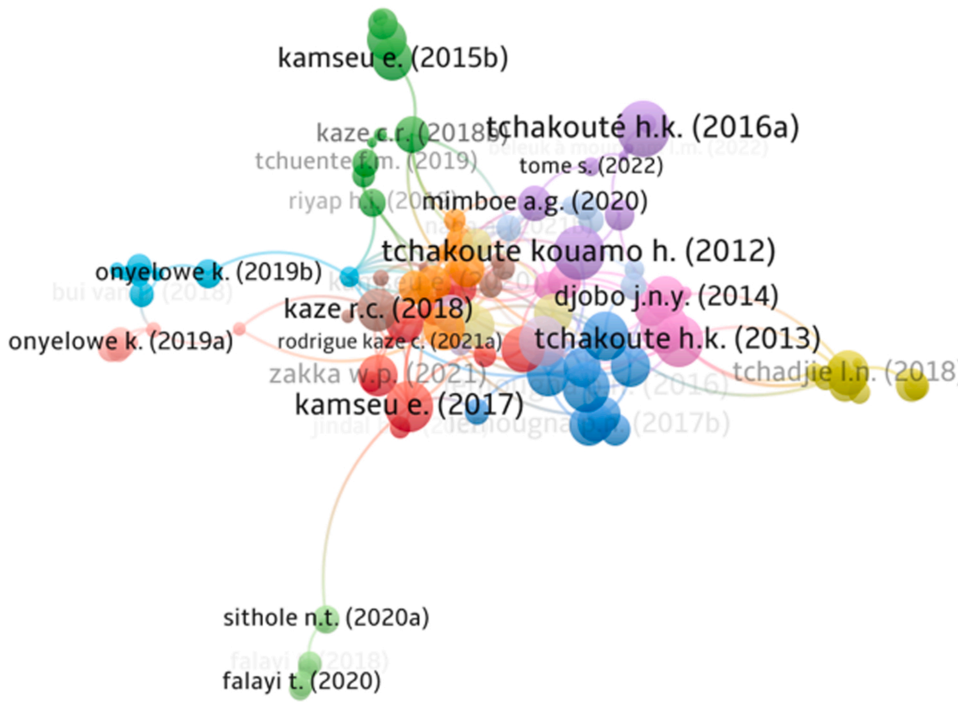

Fig. 5. Network visualization of the most cited publications.

Table 6
Leading SSA countries in geopolymer research.

S/N	Country	Publications	Percentage (%)	Total Citations	Average Citation	Nominal GDP Rank
1	Cameroon	117	45.53	3098	26.48	95
2	Nigeria	58	22.57	869	14.98	31
3	South Africa	44	17.12	391	8.89	39
4	Ethiopia	20	7.78	185	9.25	67
5	Kenya	7	2.72	15	2.14	64
6	Uganda	7	2.72	43	6.14	91
7	Malawi	4	1.56	20	5	149

good engineering measure of geopolymer performance under different structural applications [12,97]. The optimization of precursor materials used in unary, binary, or ternary geopolymer mixtures affects the mechanical performance and durability of geopolymers [21,23,89,120,121]. Therefore, there is a need for further understanding of the impact of geopolymer mix designs on strength development, durability, and standards development. The use of reinforcement in geopolymers is also gaining research interest to improve the mechanical and structural performance of geopolymers [8,22,122,123]. Krishna et al. [112] observed that the high awareness of global warming and carbon emissions has sparked interest in geopolymers. Therefore, as scientific research in geopolymers grows worldwide, it is believed that the level of research funding, industrial implementation, collaboration, and number of publications and citations in the field of geopolymers in SSA will also increase.

5. Limitations

The current study used the Scopus database only which may have limited the amount of data retrieved. The retrieved publications were in English thus excluding those which might be in different languages. Furthermore, the search query only comprised the keyword 'geopolymer'. Therefore, further study can be conducted incorporating alternative databases, different network mapping software, different languages, and keywords such as alkali-activated materials, green cement, and geocement, to ascertain an exhaustive retrieval of literature.

6. Conclusions

This study conducted a bibliometric analysis of the available literature data on geopolymer research to examine its trends and patterns and to broaden its implementation in Sub-Saharan Africa. The Scopus database was used to extract 251 relevant records in the last 10 years for network visualization in VOSviewer software. Geopolymer research remains underexplored in Sub-Saharan Africa contributing less than 4.3% of global publications. This agrees with Matsimbe et al. [11] and Olonade [82] who observed that geopolymer research is still emerging in most African countries. Therefore, this validates the need to expand geopolymer research in Sub-Saharan Africa through capacity building, financial support, and setting up local research centres and foreign joint ventures. Sub-Saharan Africa is now prioritizing investment in scientific research and innovation to boost its socio-economic development, transition to knowledge-driven economies, and competitively level up the knowledge base with regional and international partners. Thus, most Sub-Saharan African countries have incorporated geopolymer research in their agenda as evidenced by the gradual growth in publications output. The growing interest in the circular economy, solid waste management, and adherence to sustainable development goals 9, 11, 12, and 13 has made a significant impact on the growing interest in

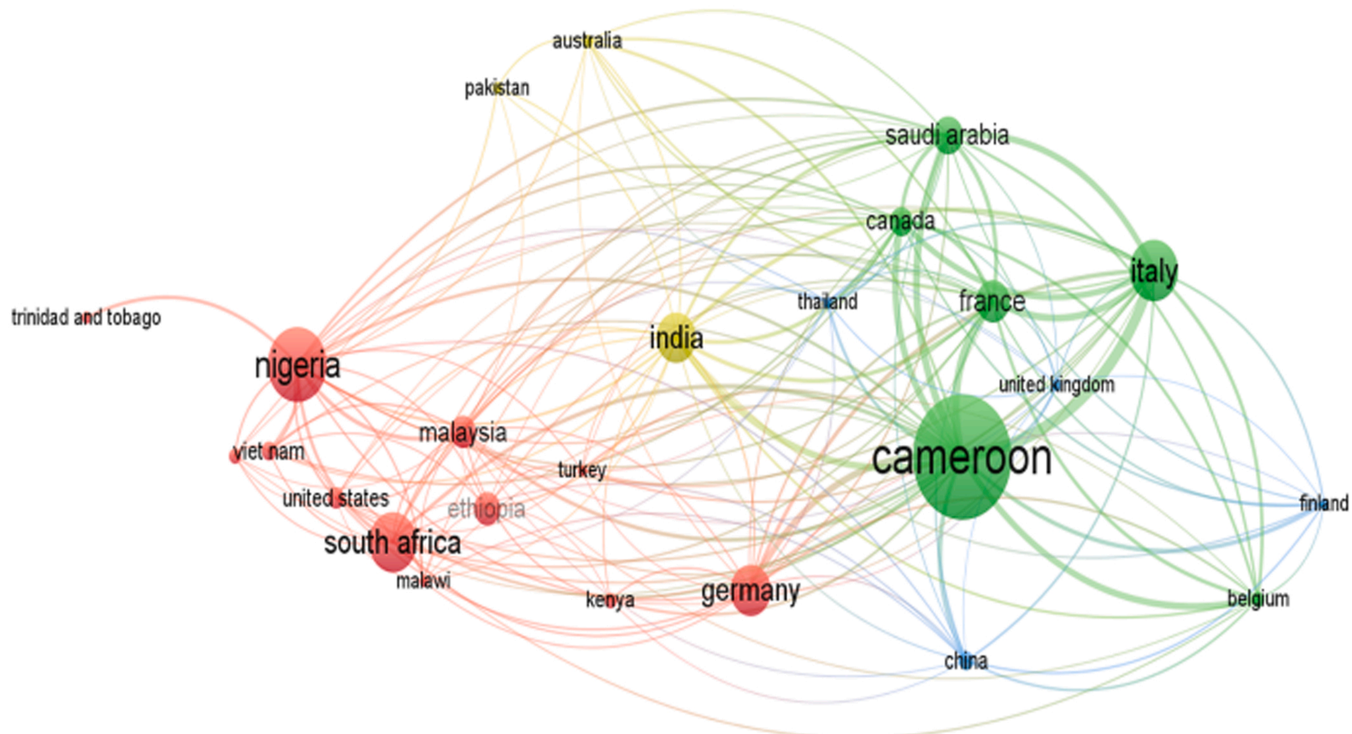

Fig. 6. Network visualization of leading SSA countries and other continents.

geopolymers. The contribution made by the present study to geopolymer literature comprises the dissection of research trends, the identification of prime researchers and bridging platforms, and future research concepts. Emerging researchers in geopolymers will benefit from the developed network visualization and statistical evaluation by giving them an updated guide on the current research trend and progress in geopolymers. The key study findings are summarized as follows:

i. The top 4 popular journals for geopolymer publications are Construction and Building Materials, Silicon, Case Studies in Construction Materials, and Materials. Most authors are citing articles from the journals Construction and Building Materials, Ceramics International, Case Studies in Construction Materials, and Journal of Building Engineering.
ii. The assessment of keywords used in geopolymer research shows that Geopolymers, Inorganic polymers, and Compressive strength are the most occurring keywords. The keywords can help new researchers easily identify research themes in search engines.
iii. The assessment of authors shows that Elie Kamseu, Cyriaque Rodrigue Kaze, and Herve Kouamo Tchakoute have the highest number of publications. The top cited authors are Elie Kamseu, Herve Kouamo Tchakoute, and Uphie Chinje Melo.
iv. The top 3 most cited publications are articles [101,102], and [103].
v. The top 3 countries leading in geopolymer publications and citations are Cameroon, Nigeria, and South Africa.

CRediT authorship contribution statement

Jabulani Matsimbe: Conceptualization, Methodology, Software, Investigation, Writing – original draft. Megersa Dinka: Conceptualization, Methodology, Validation, Writing – review & editing , Project administration. **David Olukanni:** Conceptualization, Methodology, Validation, Writing – review & editing, Project administration. **Innocent Musonda:** Validation, Writing – review & editing, Project administration

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This research is funded by the Intra-Africa Mobility Scheme of the European Union in partnership with the African Union in the framework of the project 624204-PANAF-1–2020-1-ZA-PANAF-MOBAF under the Africa Sustainable Infrastructure Mobility (ASIM) scheme. Opinions and conclusions are those of the authors and are not necessarily attributable to ASIM. The work is part of collaborative research at the Centre of Applied Research and Innovation in the Built Environment (CARINBE).

References

[1] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry, Cem. Concr. Res vol. 114 (2018) 2–26, https://doi.org/10.1016/j.cemconres.2018.03.015.

[2] W. Hu, Y. Ma, M. Koehler, H. Gong, B. Huang, Mix design optimization and early strength prediction of unary and binary geopolymer from multiple waste streams, J. Hazard. Mater. vol. 403 (2021), 123632, https://doi.org/10.1016/j.jhazmat.2020.123632.

[3] E. de Lena, et al., Techno-economic analysis of calcium looping processes for low CO_2 emission cement plants, Int. J. Greenh. Gas Control vol. 82 (2019) 244–260, https://doi.org/10.1016/j.ijggc.2019.01.005.

[4] J.G. Olivier, G. Janssens-Maenhout, M. Muntean, and J.A.H.W. Peters, "Trends in Global Co2 Emissions: 2016 Report, The Hague: Pbl CO2 Netherlands Environmental Assessment Agency; Ispra: European Commission," 2016.

[5] M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: a scientific evolution analysis, J. Build. Eng. vol. 44 (2021), 102704, https://doi.org/10.1016/j.jobe.2021.102704.

[6] M. Valente, M. Sambucci, A. Sibai, Geopolymers vs. cement matrix materials: how nanofiller can help a sustainability approach for smart construction

applications—a review, Nanomaterials vol. 11 (8) (2021) 2007, https://doi.org/10.3390/nano11082007.
[7] C. Kaze, J. Nemaleu, E. Kamseu, F. Chinje, F. Andreola, C. Leonelli, Towards optimization of mechanical and microstructural performances of Fe-rich laterite geopolymer binders cured at room temperature by varying the activating solution, RSC Adv. vol. 12 (52) (2022) 33737–33750.
[8] K. Zerfu, J.J. Ekaputri, The effect of reinforcement ratio on the flexural performance of alkali-activated fly ash-based geopolymer concrete beam, Heliyon vol. 8 (12) (2022), e12015, https://doi.org/10.1016/j.heliyon.2022.e12015.
[9] J. Labrincha et al., "From NORM by-products to building materials," in Naturally Occurring Radioactive Materials in Construction, Elsevier, 2017, pp. 183–252. doi: 10.1016/B978–0-08–102009-8.00007–4.
[10] J.L. Provis, "Geopolymers and other alkali activated materials: why, how, and what, Mater. Struct. vol. 47 (1–2) (2014) 11–25, https://doi.org/10.1617/s11527-013-0211-5.
[11] J. Matsimbe, M. Dinka, D. Olukanni, I. Musonda, A bibliometric analysis of research trends in geopolymer, Materials vol. 15 (19) (2022) 6979, https://doi.org/10.3390/ma15196979.
[12] J. Matsimbe, M. Dinka, D. Olukanni, I. Musonda, Geopolymer: a systematic review of methodologies, Materials vol. 15 (19) (2022) 6852, https://doi.org/10.3390/ma15196852.
[13] B.C. McLellan, R.P. Williams, J. Lay, A. van Riessen, G.D. Corder, Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement, J. Clean. Prod. vol. 19 (9–10) (2011) 1080–1090, https://doi.org/10.1016/j.jclepro.2011.02.010.
[14] A. Mellado, C. Catalán, N. Bouzón, M.V. Borrachero, J.M. Monzó, J. Payá, Carbon footprint of geopolymeric mortar: study of the contribution of the alkaline activating solution and assessment of an alternative route, RSC Adv. vol. 4 (45) (2014) 23846–23852, https://doi.org/10.1039/C4RA03375B.
[15] L.K. Turner, F.G. Collins, Carbon dioxide equivalent (CO_2-e) emissions: a comparison between geopolymer and OPC cement concrete, Constr. Build. Mater. vol. 43 (2013) 125–130, https://doi.org/10.1016/j.conbuildmat.2013.01.023.
[16] R.B.E. Boum, et al., Thermal behaviour of metakaolin–bauxite blends geopolymer: microstructure and mechanical properties, SN Appl. Sci. vol. 2 (8) (2020) 1358, https://doi.org/10.1007/s42452-020-3138-9.
[17] C.R. Kaze, et al., Thermal behaviour and microstructural evolution of metakaolin and meta-halloysite-based geopolymer binders: a comparative study, J. Therm. Anal. Calorim. vol. 147 (3) (2022) 2055–2071, https://doi.org/10.1007/s10973-021-10555-2.
[18] P. Sturm, G.J.G. Gluth, C. Jäger, H.J.H. Brouwers, H.-C. Kühne, Sulfuric acid resistance of one-part alkali-activated mortars, Cem. Concr. Res. vol. 109 (2018) 54–63, https://doi.org/10.1016/j.cemconres.2018.04.009.
[19] L.S. Wong, Durability performance of geopolymer concrete: a review, Polymers vol. 14 (5) (2022) 868, https://doi.org/10.3390/polym14050868.
[20] S.S. Hossain, P.K. Roy, C.-J. Bae, Utilization of waste rice husk ash for sustainable geopolymer: A review, Constr. Build. Mater. vol. 310 (2021), 125218, https://doi.org/10.1016/j.conbuildmat.2021.125218.
[21] S. Oyebisi, et al., Sustainability assessment of geopolymer concrete synthesized by slag and corncob ash, Case Stud. Constr. Mater. vol. 17 (2022), e01665, https://doi.org/10.1016/j.cscm.2022.e01665.
[22] N. Shehata, O.A. Mohamed, E.T. Sayed, M.A. Abdelkareem, A.G. Olabi, Geopolymer concrete as green building materials: Recent applications, sustainable development and circular economy potentials, Sci. Total Environ. vol. 836 (2022), 155577, https://doi.org/10.1016/j.scitotenv.2022.155577.
[23] A.R.G. de Azevedo, et al., Circular economy and durability in geopolymers ceramics pieces obtained from glass polishing waste, Int. J. Appl. Ceram. Technol. vol. 18 (6) (2021) 1891–1900, https://doi.org/10.1111/ijac.13780.
[24] A. Danish, et al., Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: a review, J. Build. Eng. vol. 58 (2022), 105005, https://doi.org/10.1016/j.jobe.2022.105005.
[25] J. Davidovits, Geopolymers—Inorganic polymeric new materials, J. Therm. Anal. vol. 37 (1991) 1633–16556.
[26] J. Davidovits, Geopolymer Chemistry and Applications, 5th ed. Saint-Quentin, France: Institut Géopolymère, 2020.
[27] M.T. Marvila, A.R.G. de Azevedo, C.M.F. Vieira, Reaction mechanisms of alkali-activated materials, Rev. IBRACON De. Estrut. e Mater. vol. 14 (3) (2021), https://doi.org/10.1590/s1983-41952021000300009.
[28] F. Pacheco-Torgal, J.A. Labrincha, C. Leonelli, A. Palomo, P. Chindaprasirt, Handbook of Alkali-Activated Cements, Mortars and Concretes, Elsevier, 2015, https://doi.org/10.1016/C2013-0-16511-7.
[29] M. Nodehi, V.M. Taghvaee, Alkali-activated materials and geopolymer: a review of common precursors and activators addressing circular economy, Circ. Econ. Sustain. vol. 2 (1) (2022) 165–196, https://doi.org/10.1007/s43615-021-00029-w.
[30] A. Adesina, et al., Fresh and mechanical properties overview of alkali-activated materials made with glass powder as precursor, Clean. Mater. vol. 3 (2022), 100036, https://doi.org/10.1016/j.clema.2021.100036.
[31] J.L. Provis, A. Palomo, C. Shi, Advances in understanding alkali-activated materials, Cem. Concr. Res vol. 78 (2015) 110–125, https://doi.org/10.1016/j.cemconres.2015.04.013.
[32] C. Shi, D. Roy, P. Krivenko, Alkali-Activated Cements and Concretes, CRC Press, 2003, https://doi.org/10.1201/9781482266900.
[33] J. L van D.J.S.J. Provis Alkali activated materials state-of-the-art report, RILEM TC 224-AAM Springe /RILEM, Dordr. 2014.
[34] P. Krivenko, Why alkaline activation – 60 years of the theory and practice of alkali-activated materials, J. Ceram. Sci. Technol. (2017).
[35] R.M. Kalombe, V.T. Ojumu, C.P. Eze, S.M. Nyale, J. Kevern, L.F. Petrik, Fly ash-based geopolymer building materials for green and sustainable development, Materials vol. 13 (24) (2020) 5699, https://doi.org/10.3390/ma13245699.
[36] SANS, "SANS 1058:2012 Concrete paving blocks," 2012.
[37] SANS, "SANS 542–2004: Standard specification for the manufacture of concrete roofing tiles," 2012.
[38] A. Naghizadeh and S. Ekolu, Effect of Mix Parameters on Strength of Geopolymer Mortars - Experimental Study, in Sixth International Conference on Durability of Concrete Structure, Leeds: University of Leeds, Jul. 2018.
[39] J. Temuujin, et al., Comparative studies of alkali activated South African Class F and Mongolian Class C fly ashes, Waste Biomass Valoriz. vol. 9 (6) (2018) 1047–1060, https://doi.org/10.1007/s12649-017-9881-5.
[40] L.N. Tchadjié, S.O. Ekolu, H. Quainoo, P. Tematio, Incorporation of activated bauxite to enhance engineering properties and microstructure of volcanic ash geopolymer mortar composites, J. Build. Eng. vol. 41 (2021), 102384, https://doi.org/10.1016/j.jobe.2021.102384.
[41] N.Z.N. Ndlovu, R.N.M. Missengue, L.F. Petrik, T. Ojumu, Synthesis and characterization of faujasite zeolite and geopolymer from South African coal fly ash, J. Environ. Eng. vol. 143 (9) (2017), https://doi.org/10.1061/(ASCE)EE.1943-7870.0001212.
[42] R. Si, S. Guo, Q. Dai, J. Wang, Atomic-structure, microstructure and mechanical properties of glass powder modified metakaolin-based geopolymer, Constr. Build. Mater. vol. 254 (2020), 119303, https://doi.org/10.1016/j.conbuildmat.2020.119303.
[43] M.R. El-Naggar, M.I. El-Dessouky, Re-use of waste glass in improving properties of metakaolin-based geopolymers: Mechanical and microstructure examinations, Constr. Build. Mater. vol. 132 (2017) 543–555, https://doi.org/10.1016/j.conbuildmat.2016.12.023.
[44] G. Ogwang, P.W. Olupot, H. Kasedde, E. Menya, H. Storz, Y. Kiros, Experimental evaluation of rice husk ash for applications in geopolymer mortars, J. Bioresour. Bioprod. vol. 6 (2) (2021) 160–167, https://doi.org/10.1016/j.jobab.2021.02.008.
[45] K.A. Buyondo, P.W. Olupot, J.B. Kirabira, A.A. Yusuf, Optimization of production parameters for rice husk ash-based geopolymer cement using response surface methodology, Case Stud. Constr. Mater. vol. 13 (2020), e00461, https://doi.org/10.1016/j.cscm.2020.e00461.
[46] T. Falayi, Sustainable solidification of ferrochrome slag through geopolymerisation: a look at the effect of curing time, type of activator and liquid solid ratio, Sustain. Environ. Res. vol. 29 (1) (2019) 21, https://doi.org/10.1186/s42834-019-0022-7.
[47] T. Falayi, A comparison between fly ash- and basic oxygen furnace slag-modified gold mine tailings geopolymers, Int. J. Energy Environ. Eng. vol. 11 (2) (2020) 207–217, https://doi.org/10.1007/s40095-019-00328-x.
[48] N.T. Sithole, F. Ntuli, F. Okonta, Fixed bed column studies for decontamination of acidic mineral effluent using porous fly ash-basic oxygen furnace slag based geopolymers, Min. Eng. vol. 154 (2020), 106397, https://doi.org/10.1016/j.mineng.2020.106397.
[49] R. Roopchund, J. Andrew, B. Sithole, Using cellulose nanocrystals to improve the mechanical properties of fly ash-based geopolymer construction materials, Eng. Sci. Technol. Int. J. vol. 25 (2022), 100989, https://doi.org/10.1016/j.jestch.2021.04.008.
[50] C. Rahmawati, S. Aprilia, T. Saidi, T.B. Aulia, Current development of geopolymer cement with nanosilica and cellulose nanocrystals, J. Phys. Conf. Ser. vol. 1783 (1) (2021), 012056, https://doi.org/10.1088/1742-6596/1783/1/012056.
[51] Y. Cao, P. Zavattieri, J. Youngblood, R. Moon, J. Weiss, The relationship between cellulose nanocrystal dispersion and strength, Constr. Build. Mater. vol. 119 (2016) 71–79, https://doi.org/10.1016/j.conbuildmat.2016.03.077.
[52] M.K. Dludlu, B. Oboirien, R. Sadiku, Micostructural and mechanical properties of geopolymers synthesized from three coal fly ashes from South Africa, Energy Fuels vol. 31 (2) (2017) 1712–1722, https://doi.org/10.1021/acs.energyfuels.6b02454.
[53] S. Huang, et al., Plastic waste management strategies and their environmental aspects: a scientometric analysis and comprehensive review, Int. J. Environ. Res. Public Health vol. 19 (8) (2022) 4556, https://doi.org/10.3390/ijerph19084556.
[54] H.A. Alkadhim, et al., Knowledge mapping of the literature on fiber-reinforced geopolymers: a scientometric review, Polymers vol. 14 (22) (2022) 5008, https://doi.org/10.3390/polym14225008.
[55] H. Yang, et al., A comprehensive overview of geopolymer composites: a bibliometric analysis and literature review, Case Stud. Constr. Mater. vol. 16 (2022), e00830, https://doi.org/10.1016/j.cscm.2021.e00830.
[56] Q. Tian, Y. Pan, Y. Bai, S. Yao, S. Sun, A bibliometric analysis of research progress and trends on fly ash-based geopolymer, Materials vol. 15 (14) (2022) 4777, https://doi.org/10.3390/ma15144777.
[57] W.P. Zakka, N.H. Abdul Shukor Lim, M. Chau Khun, A scientometric review of geopolymer concrete, J. Clean. Prod. vol. 280 (2021), 124353, https://doi.org/10.1016/j.jclepro.2020.124353.
[58] M.N. Amin, W. Ahmad, K. Khan, M.M. Sayed, Mapping research knowledge on rice husk ash application in concrete: a scientometric review, Materials vol. 15 (10) (2022) 3431, https://doi.org/10.3390/ma15103431.
[59] A. Sharma, P. Punia, S. Dahiya, A. Ohlan, R. Punia, A.S. Maan, Bibliometric analysis of tin disulphide nanomaterials, Mater. Today Proc. (2022), https://doi.org/10.1016/j.matpr.2022.08.341.
[60] Y. Agbodjan, J. Wang, Y. Cui, Z. Liu, Z. Luo, Bibliometric analysis of zero energy building research, challenges and solutions, Sol. Energy vol. 244 (2022) 414–433, https://doi.org/10.1016/j.solener.2022.08.061.

[61] J. Mhlanga, T.C. Haupt, C. Loggia, Shaping circular economy in the built environment in Africa. A bibliometric analysis, J. Eng. Des. Technol. (2022), https://doi.org/10.1108/JEDT-03-2022-0175.
[62] A. Det Udomsap, P. Hallinger, A bibliometric review of research on sustainable construction, 1994–2018, J. Clean. Prod. vol. 254 (2020), 120073, https://doi.org/10.1016/j.jclepro.2020.120073.
[63] Y. Cao, Y. Cui, X. Yu, T. Li, I.-S. Chang, J. Wu, Bibliometric analysis of phosphogypsum research from 1990 to 2020 based on literatures and patents, Environ. Sci. Pollut. Res. vol. 28 (47) (2021) 66845–66857, https://doi.org/10.1007/s11356-021-15237-y.
[64] T.L. Bambo, A. Pouris, Bibliometric analysis of bioeconomy research in South Africa, Scientometrics vol. 125 (1) (2020) 29–51, https://doi.org/10.1007/s11192-020-03626-y.
[65] M. Cetin, B. Long, M. Gottlieb, A 10-year bibliometric analysis of publications in emergency medicine, Am. J. Emerg. Med vol. 58 (2022) 215–222, https://doi.org/10.1016/j.ajem.2022.06.016.
[66] N. Ahmad et al., "Cloud Computing Trends and Cloud Migration Tuple," 2020, pp. 737–745. doi: 10.1007/978–981-15–3172-9_69.
[67] Y. Chen, M. Lin, D. Zhuang, Wastewater treatment and emerging contaminants: bibliometric analysis, Chemosphere vol. 297 (2022), 133932, https://doi.org/10.1016/j.chemosphere.2022.133932.
[68] R.M. Andrew, Global CO_2 emissions from cement production, 1928–2017, Earth Syst. Sci. Data vol. 10 (4) (2018) 2213–2239, https://doi.org/10.5194/essd-10-2213-2018.
[69] G. Kürklü, G. Görhan, Investigation of usability of quarry dust waste in fly ash-based geopolymer adhesive mortar production, Constr. Build. Mater. vol. 217 (2019) 498–506, https://doi.org/10.1016/j.conbuildmat.2019.05.104.
[70] Department of Science and Innovation, "South African National Survey of Research and Experimental Development," Republic of South Africa, 2022. Accessed: Feb. 23, 2023. [Online]. Available: https://www.dst.gov.za/index.php/documents/r-d-reports/13-rd-statistical-report-2020–21/file.
[71] Worldometer, "World Population Prospects - Africa Population," Department of Economic and Social Affairs, Population Division, Apr. 10, 2023.
[72] A. Bakilana 7 facts about population in Sub-Saharan Africa World Bank Blogs Oct. 29, 2015.
[73] D. Juju et al., "Sustainability Challenges in Sub-Saharan Africa in the Context of the Sustainable Development Goals (SDGs)," 2020, pp. 3–50. doi: 10.1007/978–981-15–4458-3_1.
[74] World Bank, Poverty and Shared Prosperity 2022: Correcting Course. Washington DC: The World Bank, 2022. doi: 10.1596/978–1-4648–1893-6.
[75] L. Li, W. Sun, W. Hu, Y. Sun, Impact of natural and social environmental factors on building energy consumption: Based on bibliometrics, J. Build. Eng. vol. 37 (2021), 102136, https://doi.org/10.1016/j.jobe.2020.102136.
[76] G.C. Nobre, E. Tavares, Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study, Scientometrics vol. 111 (1) (2017) 463–492, https://doi.org/10.1007/s11192-017-2281-6.
[77] B. Verrall, C.M. Pickering, Alpine vegetation in the context of climate change: A global review of past research and future directions, Sci. Total Environ. vol. 748 (2020), 141344, https://doi.org/10.1016/j.scitotenv.2020.141344.
[78] H.B. Adedayo, S.A. Adio, B.O. Oboirien, Energy research in Nigeria: a bibliometric analysis, Energy Strategy Rev. vol. 34 (2021), 100629, https://doi.org/10.1016/j.esr.2021.100629.
[79] P. Mongeon, A. Paul-Hus, The journal coverage of Web of Science and Scopus: a comparative analysis, Scientometrics vol. 106 (1) (2016) 213–228, https://doi.org/10.1007/s11192-015-1765-5.
[80] Leiden University, "VOSviewer: visualizing scientific landscapes," 2018.
[81] N.J. van Eck, L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics vol. 84 (2) (2010) 523–538, https://doi.org/10.1007/s11192-009-0146-3.
[82] K.A. Olonade, H. Mohammed, Review of selected bio-wastes as potential materials for alkali-activation for cement-based products, Niger. J. Technol. Dev. vol. 16 (3) (2019) 120, https://doi.org/10.4314/njtd.v16i3.5.
[83] Stats SA, "Sustainable Development Goals: Baseline report 2017," 2017.
[84] UN-Habitat, "Global Report on Human Settlements 2011: Cities and Climate Change," 2011.
[85] S.A.J. Ahmad, I.M. Abdel-Magid, A. Hussain, Comparison among journal impact factor, SCimago journal rank indicator, eigenfactor score and h5-index of environmental engineering journals, Collnet J. Scientometr. Inf. Manag. vol. 11 (1) (2017) 133–151, https://doi.org/10.1080/09737766.2016.1266807.
[86] C. Kaze, et al., Lateritic soils based geopolymer materials: a review, Constr. Build. Mater. vol. 344 (2022), 128157, https://doi.org/10.1016/j.conbuildmat.2022.128157.
[87] I. Phummiphan, S. Horpibulsuk, R. Rachan, A. Arulrajah, S.-L. Shen, P. Chindaprasirt, High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material, J. Hazard. Mater. vol. 341 (2018) 257–267, https://doi.org/10.1016/j.jhazmat.2017.07.067.
[88] C. Kaze, et al., Characterization and performance evaluation of laterite based geopolymer binder cured at different temperatures, Constr. Build. Mater. vol. 270 (2021), 121443, https://doi.org/10.1016/j.conbuildmat.2020.121443.
[89] K.C. Onyelowe, M.E. Onyia, F.I. Aneke, D. Bui-Van, K.M. Rollins, Assessment of compressive strength, durability, and erodibility of quarry dust-based geopolymer cement stabilized expansive soil, Multiscale Multidiscip. Model. Exp. Des. vol. 5 (1) (2022) 81–90, https://doi.org/10.1007/s41939-021-00104-7.
[90] K. Chen, et al., Modeling and optimization of fly ash–slag-based geopolymer using response surface method and its application in soft soil stabilization, Constr. Build. Mater. vol. 315 (2022), 125723, https://doi.org/10.1016/j.conbuildmat.2021.125723.
[91] A.L. Murmu, N. Dhole, A. Patel, Stabilisation of black cotton soil for subgrade application using fly ash geopolymer, Road. Mater. Pavement Des. vol. 21 (3) (2020) 867–885, https://doi.org/10.1080/14680629.2018.1530131.
[92] P.N. Lemougna, U.F.C. Melo, E. Kamseu, A.B. Tchamba, Laterite based stabilized products for sustainable building applications in tropical countries: review and prospects for the case of cameroon, Sustainability vol. 3 (1) (2011) 293–305, https://doi.org/10.3390/su3010293.
[93] J.N.Y. Djobo, A. Elimbi, H.K. Tchakouté, S. Kumar, Volcanic ash-based geopolymer cements/concretes: the current state of the art and perspectives, Environ. Sci. Pollut. Res. vol. 24 (5) (2017) 4433–4446, https://doi.org/10.1007/s11356-016-8230-8.
[94] J. Nemaleu, et al., Synthesis and characterization of eco-friendly mortars made with RHA-NaOH activated fly ash as binder at room temperature, Clean. Mater. vol. 1 (2021), 100010, https://doi.org/10.1016/j.clema.2021.100010.
[95] S.N. Tantono, P.D. Belibi Belibi, J. Baenla, A. Elimbi, Alkaline and acid activations of calcined laterites: a comparative study, Silicon (2022), https://doi.org/10.1007/s12633-022-02211-7.
[96] P. Venyite, et al., Effect of combined metakaolin and basalt powder additions to laterite-based geopolymers activated by rice husk ash (RHA)/NaOH solution, Silicon vol. 14 (4) (2022) 1643–1662, https://doi.org/10.1007/s12633-021-00950-7.
[97] C. Kaze, S. Jiofack, Ö. Cengiz, T.S. Alomayri, A. Adesina, H. Rahier, Reactivity and mechanical performance of geopolymer binders from metakaolin/meta-halloysite blends, Constr. Build. Mater. vol. 336 (2022), 127546, https://doi.org/10.1016/j.conbuildmat.2022.127546.
[98] E. Kamseu, et al., Pore network and microstructure in the prediction of heat flux transport in sponge-like geopolymers for thermal insulation, J. Therm. Anal. Calorim. vol. 147 (22) (2022) 12329–12344, https://doi.org/10.1007/s10973-022-11396-3.
[99] Z.N.M. Ngouloure, E. Kamseu, L.M.B. à Moungam, H.K. Tchakoute, L. Valentini, C. Leonelli, Design of porous Geopolymers for hygrothermal applications: role of nano and meso porosity, Silicon vol. 14 (15) (2022) 10045–10059, https://doi.org/10.1007/s12633-022-01741-4.
[100] H.K. Tchakouté, S.J.K. Melele, C.P. Nanseu-Njiki, C.H. Rüscher, Semi-adiabatic calorimetry to determine the temperature and the time of the formation of faujasite and geopolymer gels in the composites prepared at room temperature and the investigation of the properties of the hardened composites, Silicon vol. 14 (9) (2022) 4669–4681, https://doi.org/10.1007/s12633-021-01267-1.
[101] H.K. Tchakouté, C.H. Rüscher, S. Kong, E. Kamseu, C. Leonelli, Geopolymer binders from metakaolin using sodium waterglass from waste glass and rice husk ash as alternative activators: a comparative study, Constr. Build. Mater. vol. 114 (2016) 276–289, https://doi.org/10.1016/j.conbuildmat.2016.03.184.
[102] H. Tchakoute, A. Elimbi, J.A. Mbey, C.J. Ngally Sabouang, D. Njopwouo, The effect of adding alumina-oxide to metakaolin and volcanic ash on geopolymer products: a comparative study, Constr. Build. Mater. vol. 35 (2012) 960–969, https://doi.org/10.1016/j.conbuildmat.2012.04.023.
[103] H. Tchakoute, A. Elimbi, E. Yanne, C.N. Djangang, Utilization of volcanic ashes for the production of geopolymers cured at ambient temperature, Cem. Concr. Compos vol. 38 (2013) 75–81, https://doi.org/10.1016/j.cemconcomp.2013.03.010.
[104] L.N. Tchadjié, et al., Potential of using granite waste as raw material for geopolymer synthesis, Ceram. Int. vol. 42 (2) (2016) 3046–3055, https://doi.org/10.1016/j.ceramint.2015.10.091.
[105] P. Awoyera, A. Adesina, A critical review on application of alkali activated slag as a sustainable composite binder, Case Stud. Constr. Mater. vol. 11 (2019), e00268, https://doi.org/10.1016/j.cscm.2019.e00268.
[106] E. Kamseu, et al., Substitution of sodium silicate with rice husk ash-NaOH solution in metakaolin based geopolymer cement concerning reduction in global warming, J. Clean. Prod. vol. 142 (2017) 3050–3060, https://doi.org/10.1016/j.jclepro.2016.10.164.
[107] M. Kahn, A bibliometric analysis of South Africa's scientific outputs – some trends and implications, S Afr. J. Sci. vol. 107 (1/2) (2011), https://doi.org/10.4102/sajs.v107i1/2.406.
[108] OECD The compendium of international organisation's practices: working towards more effective international instruments Paris.: Organ. Econ. Coop. Dev. 2022.
[109] B.C. Mendes, et al., Application of eco-friendly alternative activators in alkali-activated materials: a review, J. Build. Eng. vol. 35 (2021), 102010, https://doi.org/10.1016/j.jobe.2020.102010.
[110] P.N. Lemougna, N. Dilissen, G.M. Hernandez, F. Kingne, J. Gu, H. Rahier, Effect of sodium disilicate and metasilicate on the microstructure and mechanical properties of one-part alkali-activated copper slag/ground granulated blast furnace slag, Materials vol. 14 (19) (2021) 5505, https://doi.org/10.3390/ma14195505.
[111] M. Elzeadani, D.V. Bompa, A.Y. Elghazouli, One part alkali activated materials: a state-of-the-art review, J. Build. Eng. vol. 57 (2022), 104871, https://doi.org/10.1016/j.jobe.2022.104871.
[112] R.S. Krishna, et al., A review on developments of environmentally friendly geopolymer technology, Materialia vol. 20 (2021), 101212, https://doi.org/10.1016/j.mtla.2021.101212.
[113] B.S. Mohammed, S. Haruna, M. Mubarak bn Abdul Wahab, M.S. Liew, Optimization and characterization of cast in-situ alkali-activated pastes by response surface methodology, Constr. Build. Mater. vol. 225 (2019) 776–787, https://doi.org/10.1016/j.conbuildmat.2019.07.267.

[114] M. Nawaz, A. Heitor, M. Sivakumar, Geopolymers in construction - recent developments, Constr. Build. Mater. vol. 260 (2020), 120472, https://doi.org/10.1016/j.conbuildmat.2020.120472.

[115] M.S. Saif, M.O.R. El-Hariri, A.I. Sarie-Eldin, B.A. Tayeh, M.F. Farag, Impact of Ca + content and curing condition on durability performance of metakaolin-based geopolymer mortars, Case Stud. Constr. Mater. vol. 16 (2022), e00922, https://doi.org/10.1016/j.cscm.2022.e00922.

[116] S.H. Bong, M. Xia, B. Nematollahi, C. Shi, Ambient temperature cured 'just-add-water' geopolymer for 3D concrete printing applications, Cem. Concr. Compos vol. 121 (2021), 104060, https://doi.org/10.1016/j.cemconcomp.2021.104060.

[117] D. Vaičiukynienė, D. Nizevičienė, A. Kantautas, V. Bocullo, A. Kielė, Alkali activated paste and concrete based on of biomass bottom ash with phosphogypsum, Appl. Sci. vol. 10 (15) (2020) 5190, https://doi.org/10.3390/app10155190.

[118] T. Mashifana, J. Sebothoma, T. Sithole, Alkaline activation of basic oxygen furnace slag modified gold mine tailings for building material, Adv. Civ. Eng. vol. 2021 (2021) 1–11, https://doi.org/10.1155/2021/9984494.

[119] J.J. Kipsanai, P.M. Wambua, S.S. Namango, S. Amziane, A review on the incorporation of diatomaceous earth as a geopolymer-based concrete building resource, Materials vol. 15 (20) (2022) 7130, https://doi.org/10.3390/ma15207130.

[120] O.F. Nnaemeka, N.B. Singh, Durability properties of geopolymer concrete made from fly ash in presence of Kaolin, Mater. Today Proc. vol. 29 (2020) 781–784, https://doi.org/10.1016/j.matpr.2020.04.696.

[121] M. Zerzouri, S. Alehyen, R. Hamzaoui, L. Ziyani, A. Loukili, Durability of Moroccan fly ash-based geopolymer binder, Mater. Lett. vol. 304 (2021), 130673, https://doi.org/10.1016/j.matlet.2021.130673.

[122] E.A. Taye, J.A. Roether, D.W. Schubert, D.T. Redda, A.R. Boccaccini, Hemp fiber reinforced red mud/fly ash geopolymer composite materials: effect of fiber content on mechanical strength, Materials vol. 14 (3) (2021) 511, https://doi.org/10.3390/ma14030511.

[123] A.L. Almutairi, B.A. Tayeh, A. Adesina, H.F. Isleem, A.M. Zeyad, Potential applications of geopolymer concrete in construction: a review, Case Stud. Constr. Mater. vol. 15 (2021), e00733, https://doi.org/10.1016/j.cscm.2021.e00733.