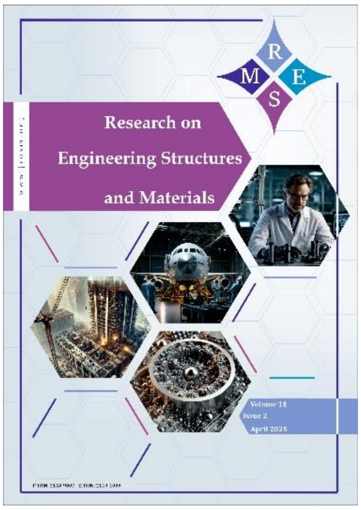
Research on Engineering Structures & Materials
www.jresm.org
Research Group



Mapping the research landscape of geopolymer concrete: Trends, gaps and future directions

Shweta Tikotkar, Sayali Sandbhor, Sanjay Kulkarni

Online Publication Date: 20 October 2025

URL: http://www.jresm.org/archive/resm2025-981ma0620rv.html

DOI: http://dx.doi.org/10.17515/ resm2025-981ma0620rv

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Tikotkar S, Sandbhor S, Kulkarni S. Mapping the research landscape of geopolymer concrete: Trends, gaps and future directions. *Res. Eng. Struct. Mater.*, 2026; 12(3): 1331-1355.

Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Review Article

Mapping the research landscape of geopolymer concrete: Trends, gaps and future directions

Shweta Tikotkar [a], Sayali Sandbhor [*,b], Sanjay Kulkarni [c]

Department of Civil Engineering, Symbiosis Institute of Technology (SIT), Pune, Symbiosis International (Deemed University), Pune, India

Article Info

Article History:

Received 20 June 2025
Accepted 16 Oct 2025

Keywords:

Geopolymer concrete;
Concrete Composite;
Carbon footprint;
Global warming;
Sustainability

Abstract

Geopolymer Concrete (GPC) contributes to the reduction of CO_2 emissions, providing an environmentally friendly alternative to Ordinary Portland Cement (OPC). This is achieved by incorporating industrial by-products such as fly ash, slag, metakaolin and silica fume. This reduces landfill waste and environmental pollution while aligning with sustainability goals. Research studies on GPC demonstrate superior durability, resistance to chemical attacks, fire and high temperatures, early strength and long-term stability. It also offers economic advantages through lower production costs and energy savings, as its manufacturing process requires less energy than traditional cement production. The bibliometric analysis will use data extracted from the Scopus database. This study includes data visualization and statistical analysis of key parameters such as subject area, year-wise publication trends, country-wise publication distribution, author-based publication details and citation analysis. The study incorporates specific metrics to support its claims, including publication count, citation count and country-by-country comparisons. It highlights notable findings such as top journals, influential authors and annual research growth rates, all of which are crucial in demonstrating the value of the study. The findings reinforce the growing consensus in the literature advocating GPC as a sustainable alternative to traditional concrete. This highlights the significant amount of research conducted in this area within the Global and Indian context, underscores the continued scope for future research. Since GPC is not yet part of building codes in many regions, optimizing factors like molarity, durability, mix ratios and self-healing properties could help replace conventional concrete in future construction.

1. Introduction

Concrete is widely used due to its ease of operation, mechanical properties, construction industry demand and low production costs. However, its production releases a ton of carbon dioxide for each ton of Portland cement production into the atmosphere [1]. Out of the total 37.8 Giga tones (Gt) CO_2 emissions, global emissions of carbon dioxide from the manufacturing of cement have crossed 1.56 billion metric tons. While China's total CO_2 emissions have increased roughly by 257%, from about 3.5 Gt CO_2 in 2000 to nearly 12.5 Gt CO_2 in 2024, making it the dominant global emitter, India, starting from 0.9 Gt CO_2, also has shown a significant rise to 3 Gt CO_2, reflecting rapid industrialization and growing energy demand [2]. While China is also leading the global charts in CO_2 emissions from cement production with 718 million metric tons of CO_2 as reported in year 2023, India is the second largest polluter from cement manufacturing after China, with its cement industry releasing 177 million metric tons of CO_2 [3,4].

*Corresponding author: sayali.sandbhor@sitpune.edu.in
[a]orcid.org/0009-0008-5142-4352; [b]orcid.org/0000-0003-2959-6023; [c]orcid.org/0000-0001-6227-5526
DOI: http://dx.doi.org/10.17515/resm2025-981ma0620rv

The construction industry recognizes the benefits of reducing OPC in concrete production and using cementitious materials such as fly ash and Ground Granulated Blast Furnace Slag (GGBS), which have environmental benefits. To solve the issue of industry by-product disposal, Davidovits J. [5] in year 1994, proposed the 100% replacement of cement with cementitious materials rich in Silica (Si) and Alumina (Al) by using Alkaline Activator (AA), forming Geopolymer Concrete (GPC). Since then, GPC has been researched for its properties, applicability and usefulness in small to large constructions. GPC exhibits high compressive strength, low drying shrinkage and exceptional resistance to chemical attacks [6], which makes it highly suitable for harsh environments such as marine structures, wastewater systems and industrial facilities [7]. The scheme in Fig. 1 shows a basic reaction pathway highlighting the main participating components of GPC. It involves solid alumina silicate materials that are mixed with liquid alkaline activators, followed by a curing regime.

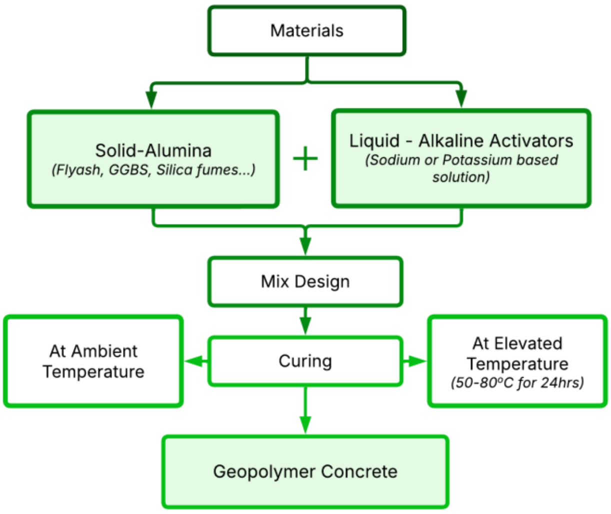


Fig. 1. Schematic of the Components of geopolymer concrete

GPC offers several benefits over conventional concrete, making it a sustainable and durable alternative in construction. By utilizing industrial by-products, it significantly lowers CO_2 emissions and reduces landfill waste. GPC is characterized by its enhanced service life, superior resistance to corrosion and fire, which ensures long term durability even in harsh environments. Its ability to repurpose industrial waste not only minimizes environmental impact but also supports a circular economy. Collectively, these benefits highlight geopolymer concrete as a green construction material that addresses both environmental sustainability and performance efficiency. Fig. 2 visually summarizes key advantages of GPC in construction.

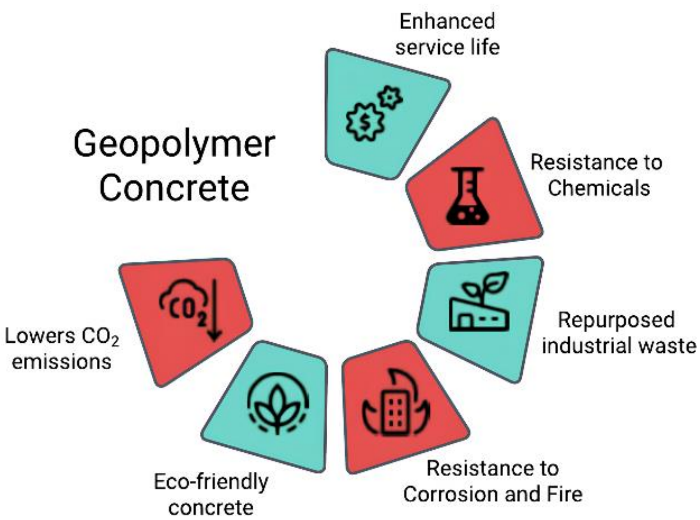


Fig. 2. Usefulness of geopolymer concrete in construction

Significant research has enhanced our understanding of GPC, factors such as mix design, curing methods and chemical activation processes. For example, studies show that the properties of fly ash based geopolymer mortars are highly dependent on the fineness and chemical composition of the source material, which requires careful adjustment of the AA [8,9]. Furthermore, the compressive strength is strongly influenced by the amount of GGBS, the alkaline solution ratio and the curing conditions [10].

A study [11] found that the behavior of GPC is controlled by several factors, such as the mix ratio and curing, unlike regular concrete, which depends primarily on its water cement ratio. However, this study did not provide standardized rules, fully explain how the reactions work, or address the challenges in optimizing properties for diverse applications. Several rigorous reviews exist on GPC, such as analysis of mix design, mechanical properties [12], systematic review of production models and sustainability [13], yet a research gap persists. Previous reviews often lack a systematic, bibliographic approach that categorizes and compares the vast body of literature. The present research study meets those needs by conducting a systematic bibliography and statistical analysis. This study systematically maps global and Indian research trends through citation metrics, GPC stands out by providing data driven critical analysis of key parameters like compressive strength, durability and thermal resistance, compared to conventional concrete. The analysis is structured by classifying previous research into distinct sets (e.g., sets A, B and C) based on database scope, allowing for a clear assessment of progress and innovation in GPC development.

1.1 Need of the Study

GPC has significant potential for advanced sustainable construction and reducing environmental challenges associated with traditional cement. However, the lack of standardized design guidelines, limited understanding of long-term sustainability and widespread adoption are hindered by serious unresolved issues, such as challenges in large scale use due to the inherent variability of geopolymer systems. To address these gaps, this study uses a systematic bibliographic analysis designed to quantitatively map and evaluate existing research trends. The method involves a structured literature search using keywords focused on three main domains: materials, properties and miscellaneous topics. Through analysis, this approach enables an accurate assessment of current knowledge, identifies research concentrations, gaps, highlights disparities between laboratory findings and industrial needs. This data driven framework aims to guide future research to standardize GPC design and facilitate its practical implementation.

1.2. Literature review

Geopolymer Concrete has emerged as one of the most promising sustainable alternatives to OPC, driven by research into its constituent materials, activator chemistry and resulting properties. The concept of “geopolymer” was introduced in the late 1970s to classify mineral polymers synthesized from silica and alumina rich precursors activated with alkaline solutions [14]. The geopolymerization process involves the dissolution of raw materials, oligomer formation and subsequent polymerization into a dense three-dimensional aluminosilicate network [15]. This reaction produces a binder capable of curing at ambient or mild heat conditions, achieving mechanical strengths comparable to OPC while offering significant environmental advantages [16]. A central focus in GPC research is the role of alkaline activators, which dissolve silica and alumina from source materials, enabling network formation. Studies demonstrate that sodium silicate, sodium hydroxide systems are particularly effective, with curing conditions and activator ratios strongly influencing mechanical performance and workability. For instance, curing at 65 °C for 24 hours has shown to optimize compressive strength, while sodium silicate contributes to higher plastic viscosity and improved early hardening [17,18]. These findings underscore how activator chemistry governs both fresh and hardened properties.

Equally important are the precursor materials, most prominently fly ash and GGBS. Fly ash, a by-product of coal combustion, is abundant and rich in aluminosilicates, making it well suited for geopolymerization [19]. Low calcium fly ash yields superior bonding and strength, whereas excess calcium can disrupt polymerization and compromise microstructural integrity [20]. Fly ash based geopolymers also demonstrate excellent durability, with low shrinkage, minimal creep, resistance to sulphate and acid attack [21]. In parallel, GGBS, a by-product of iron manufacturing, introduces latent hydraulic properties that accelerate setting and contribute to the formation of calcium–silicate hydrate gels [22,24]. Its inclusion in GPC mixtures improves strength, reduces setting times, enhances workability and increases resistance to chemical attack, making it particularly effective in harsh marine or industrial environments [25,27].

Taken together, the literature indicates that the interplay between raw material composition and alkaline activator chemistry governs the structural, mechanical and durability characteristics of GPC. Bibliometric analyses further reveal growing attention to sustainable sourcing, waste valorization and the scalability of these materials. By linking constituent properties with performance outcomes, current research provides a strong foundation for defining state of the art research, experimental parameters and advancing the application of GPC in sustainable construction practices.

2. Research Methodology

A bibliometric survey provides insights into global and research trends in India, covering subject areas of engineering and material science, straining further in parameters such as publication year, country and author. The data was collected from January 10, 2025 for the first keyword search and subsequent changes were made in the search to align with the study criteria. The period chosen for the bibliometric analysis is between year 2014 to year 2024, focusing on advancements in the field for the last ten years. Research since 2014 focuses on modern challenges such as CO_2 reduction, practical applications and cost-effective materials, reflecting current priorities. This period highlights new trends rather than old practices, ensuring that the analysis remains relevant to recent advances in sustainability and industry standards. For this study, Scopus has been chosen as the search engine due to its reliable analytics and ability to provide valuable insights that accelerate innovation. To bring consistency to the analysis, the study focuses only on English language sources, acknowledging that this may have excluded valuable findings published in other languages. Structured manual analysis is performed using the "Analyze Results" module in Scopus, based on a database search and screening protocol outlined in Table 1. Keywords for the bibliometric survey are most crucial, as even slight changes can significantly impact the search results. The survey is conducted using selected keywords divided into three sets: Set A (Materials), Set B (Properties) and Set C (Miscellaneous). These sets highlight the global adoption of GPC, provide a deeper understanding of India's status in adopting and ensuring the safety of GPC.

Table 1. Database Search Criteria

Item	Criteria for inclusion
Database	Scopus
Period	2014–2024
Language	English
Subject area	Engineering and Materials Science
Document type	Article, Conference paper, Book chapter, Review, Erratum, Retracted
Source type	Journal, Conference proceeding, Book series, Book, Trade journal

This survey (Fig. 3) focuses on classifying GPC research by material type, application, sustainability factors and performance indicators. It follows a structured process, beginning with database selection and data harvesting through keyword searches. Followed by analyze and reporting, done through careful data organization and synthesis. The next step involves downloading, organizing and manually analyzing data in the descriptive format using MS Excel along with software tools like Lucid, Canva, Iipmaps and VOS viewer, for visual clarity in charting and validation. Finally, the summary and discussion section compare GPC with conventional or other sustainable construction materials, noting advancements or setbacks unique to GPC.

Fig. 3. Methodological workflow for systematic bibliographic analysis of geopolymer research

To draw preliminary conclusions, three thematic sets of the paper are systematically assessed, each targeting specific aspects of GPC research. This triple division ensures a representative analysis of the existing literature with minimal overlap in the total count due to category of sets. The search strategy (Fig. 4) uses subgroup specific keywords, followed by common keywords "Geopolymer" OR "Geopolymer Concrete" in each set. With the selected keywords of Set-A, the search has revealed a total of 686 documents, which have been added to study the materials of GPC worldwide, whereas 220 documents are found in India. Search of keywords from set B is carried out for analyzing properties of GPC, particularly for application in the construction sector, which has 395 results globally and 114 documents in India. Set C search shows a total of 402 documents globally, whereas 146 documents are observed for miscellaneous topics in India. Details of the statistics of these three sets are further explained.

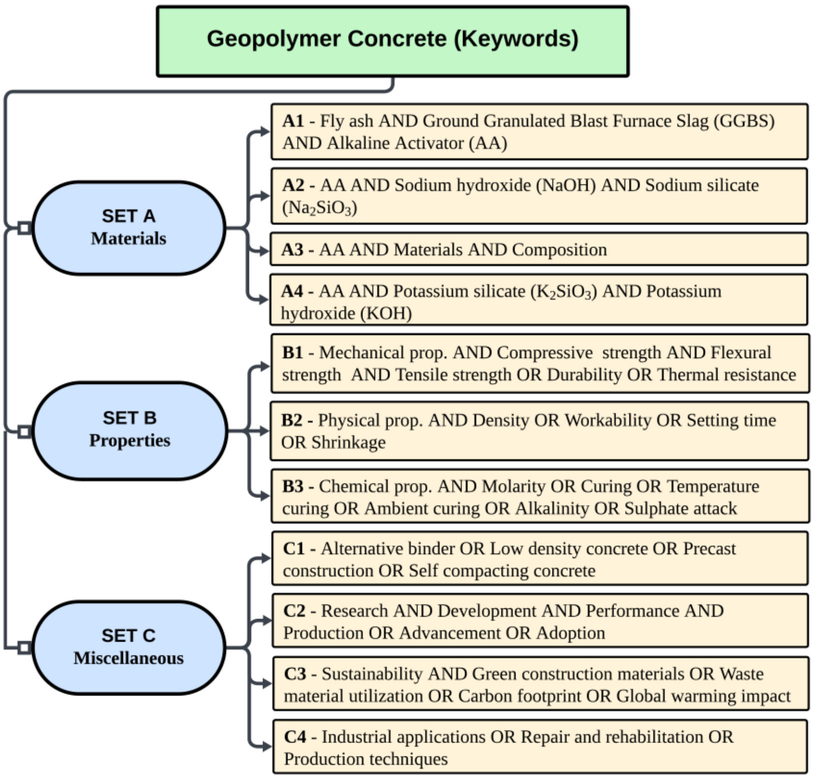


Fig. 4. Details of thematic keyword sets A, B and C and their subsets for the bibliometric survey

Fig. 4 outlines the composition of the eleven keyword sets in detail. When searching, Boolean operators like 'AND' and 'OR' are used in between keywords to improve search precision, efficiency, as well as relevance on a database by focusing on specific topics and handling complex searches effectively. The analysis is systematically organized into three primary sets (A, B and C), which are further divided into subsets. For visual clarity and quick identification in all graphical presentations, each set is given a different color: Set A (blue), Set B (red) and Set C (green). Each set likely represents a specific approach, focus area and level of rephrasing. Set A includes keywords related to materials used in GPC, grouped into smaller categories, namely Subset A1 - Fly ash AND GGBS AND Alkaline Activator (AA); Subset A2 - AA AND NaOH AND Na2SiO3; Subset A3 - AA AND Material AND Composition; Subset A4 - AA AND Potassium silicate (K2SiO3) AND Potassium hydroxide (KOH), where the sodium-based activator combination operates the most popular AA. These keywords were selected based on their practical importance in geopolymer research. Fly ash and GGBS were chosen as they are widely available, cost effective and durable binders. Sodium based activators were preferred due to their low cost and excellent reactivity with aluminosilicate materials.

Set B contains Property specific keywords with Subset B1 - Mechanical properties AND Compressive strength AND Flexural strength AND Tensile strength OR Durability OR Thermal resistance; Subset B2 - Physical properties AND Density OR Workability OR Setting time OR Shrinkage; Subset B3 - Chemical properties AND Molarity OR Curing OR Temperature curing OR Ambient curing OR Alkalinity OR Sulphate attack. Mechanical properties are the most extensively researched class due to their fundamental importance for structural applications in construction. Physical properties, including workability and setting time, critically influence both the practical implementation during placement and the long-term stability of GPC structures. Chemical properties control the required geopolymerization process, where key factors such as activator molarity (typically 8M -12M NaOH) directly control the reaction kinetics. So, treatment methods present a spectrum from energy intensive thermal treatments to more sustainable environmental approaches. This systematic classification not only reflects current research priorities but also highlights important relationships between characteristics and practical performance.

Set C contains Miscellaneous topics like; Subset C1 - Alternative binder OR Low-density concrete OR Precast construction OR Self compacting concrete; Subset C2 - Research AND development AND Performance AND Production OR advancement OR Adoption; Subset C3 - Sustainability AND Green construction material OR Waste material utilization OR Carbon footprint OR Global warming impact; Subset C4 - Industrial applications OR Repair and rehabilitation OR Production techniques. These keywords are carefully selected to explore important but often overlooked areas of GPC research. These words can be used to find solutions to material shortages, test special concrete formulations for specific applications, evaluate real world implementation capabilities and help demonstrate the suitability of materials in different construction situations. This approach provides a more comprehensive understanding of the broad applications of GPC beyond basic material properties.

3. Data Visualization and Statistical Analysis of Bibliometric Survey Outcomes

This section uses data visualization and statistical techniques to analyze key patterns in bibliometric analysis for GPC research. It examines publication distribution across subject areas, trends in research output and geographical contributions, with a particular focus on India's annual productivity, lead authors and funding sources. The analysis also identifies influential global researchers and compares national publication metrics. Through graphs, charts and quantitative summaries, this section provides a clear, concise overview of the sector's development, collaboration and intellectual focus. It also provides an evidence-based overview, which helps identify growth patterns and future research opportunities. All figures and tables in this section utilize data sourced from Scopus database, systematically presented below [28].

3.1. Documents Based on The Subject Area

A total of 2177 documents were found in the search for both Engineering and Materials Science subjects on the Scopus database. For Set A, a total of 966 documents are recorded, while 651 are recorded for Set B and 560 for Set C, combined for both sectors. The Engineering field has 1211 documents, including Set A, Set B and Set C, whereas the Material science field consists of 966 documents.

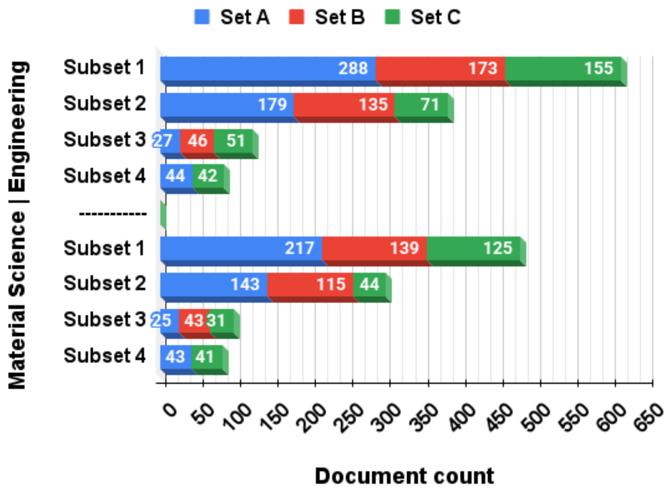


Fig. 5. Number of documents for varied subsets under Set A, B and C

The majority of the documents belong to the engineering sector across all three Sets (Fig. 5), accounting for 55.6%, while the material science sector represents 44.4%. Within the "Engineering" sector, 44.4% of the documents are from Set A, 29.2% from Set B and 26.3% from Set C. The Materials Science domain shows different proportions across keyword sets: 44.3% (Set A), 30.7% (Set B) and 24.9% (Set C) of the total publications.

Table 2. Structured differentiation of the terms based on their primary association with Engineering vs. Materials Science in geopolymer research

Term	Engineering
Carbon Footprint	Sustainability metrics
Geopolymer Mortars	Repair/coating applications
Binders (Fly Ash, GGBS)	Waste utilization, strength enhancement and workability
Curing	Process optimization
Durability	Long term infrastructure performance
Water Absorption	Porosity control for weathering
Workability	Construction practicality
Setting Time	Construction process control
Tensile Strength	Flexural design
Compressive Strength	Load bearing capacity
Bending Strength / Flexural Strength	Structural design criteria
Reinforced Concrete	Composite applications
Rheology	Flow behavior for casting/printing
Fire Resistance	Building safety standards
Acid Resistance	Durability in harsh environments
Shrinkage	Crack prevention in structures
Thermal Insulation	Energy efficient buildings
Term	**Materials Science**
Geopolymerization	Molecular scale reaction mechanisms
Silicates, Silica	Chemical bonding analysis, Silicon Dioxide (SiO_2) network formation
Alkaline Activators	Reaction kinetics
NaOH	pH dependent geopolymerization
Na_2SiO_3	Si/Al ratio optimization

Aluminosilicates	Atomic structure of precursors
Silica Fume	Pozzolanic activity
Chemical Activation	Reaction kinetics
Calcination	Precursor treatment
Molar Ratio	Stoichiometric control of reactions
Microstructure	Nanoscale morphology
Scanning Electron Microscopy (SEM)	Material characterization
Fourier Transform Infrared Spectroscopy	Chemical bond identification
X-ray Diffraction	Crystalline phase analysis
Thermogravimetric Analysis	Thermal decomposition studies
Energy Dispersive Spectroscopy	Elemental mapping
Micro structural Properties	Nanoscale morphology

Table 2 provides a clear classification of key terms in geopolymer research, distinguishing their primary alignment with materials science or engineering. The materials science approach encompasses fundamental chemistry, microstructure and synthesis. Emphasizing this, engineering focuses on applied performance, structural design and sustainability. Proper classification of these terms is crucial for accurate interdisciplinary research, ensuring accurate application in each field.

3.2 Year-Wise Publication Details

Global publication of GPC, shown in Fig. 6, has consistent growth over time in document count from 319 in 2014 to 2002 documents in the year 2024. This represents a growth rate of 20.2%, calculated using the Compound Annual Growth Rate (CAGR), the same method applied through this study, as it provides a smooth annual rate that accurately reflects long term trends by neutralizing short term fluctuations. The trendline indicates a consistent and significant increase in research output. The span of 2019-2021 indicates periods of rapid expansion, possibly due to increased investment, innovation, or adoption, whereas, the year 2021-2022 suggests temporary slowdowns, which could be due to market saturation, resource constraints, or other external factors. A noticeable dip in 2020-2022 may indicate the impact of external factors, such as the COVID-19 pandemic, which could have influenced documentation processes. Between 2021 and 2023, the upward trend continued, with a sharper increase in document numbers, potentially due to technological advancements or organizational changes.

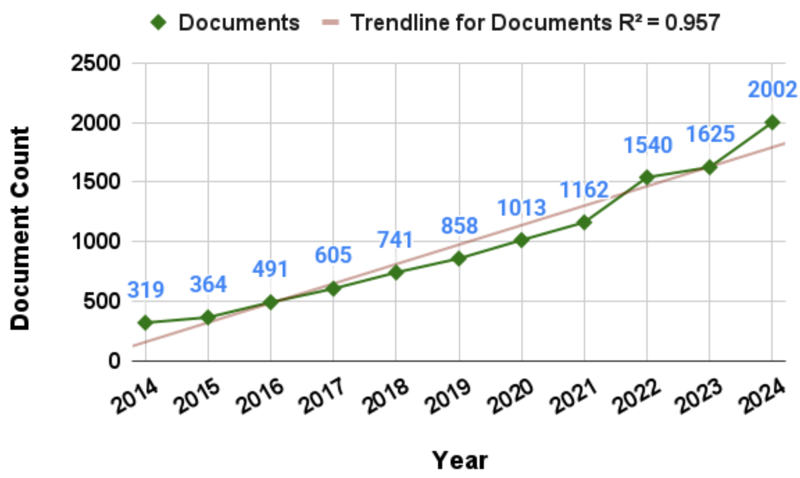


Fig. 6. Global annual publication growth in geopolymer research

Set A (Fig. 7), which consists of material specific data, shows a noticeable spike and dip over the decade. Starting with a baseline of 18 documents in 2014 across all subsets, the total number of documents grew to 80 in 2024, reflecting a growth rate of approximately +16%. This indicates a strong overall growth trend despite fluctuations.

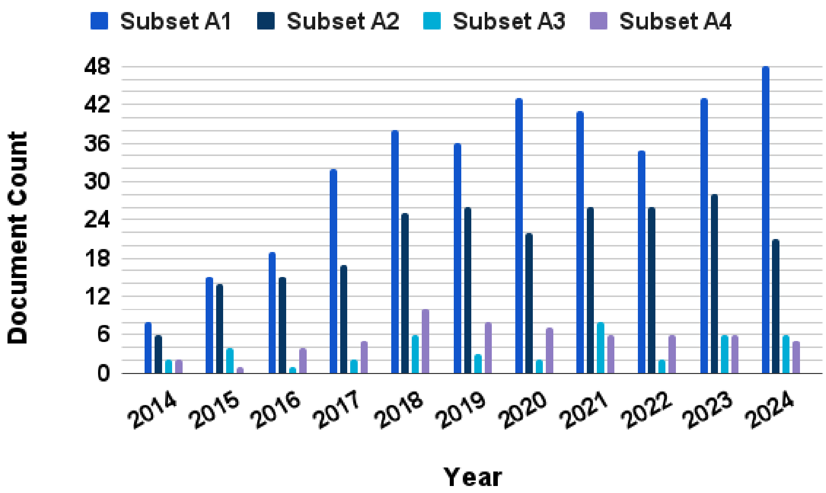


Fig. 7. Year-wise distribution of publications in Set A

- Subset A1 (Fly ash, GGBS, AA) began with 8 documents in 2014 and grew to 48 in 2024, for a total of 358 documents and a growth rate of +19.6%, showing the highest growth among all subsets.
- Subset A2 (AA, NaOH, Na_2SiO_3) started from 6 documents and reached 21, for a total of 226 documents and a growth rate of +13.3%, also demonstrating strong growth despite some fluctuations.
- Subset A3 (AA, material, composition) started from a lower count of 2 documents and grew to 6, for a total of 42 documents and a growth rate of +11.6%.
- Subset A4 (AA, K_2SiO_3, KOH) increased from 2 to 5 documents, for a total of 60 documents and a growth rate of +9.6%.

Subsets A3 and A4 have 82.5% fewer documents compared to Subsets A1 and A2, indicating significantly less activity in these areas. However, all subsets contribute to the overall growth trend, with Subset A1 leading in both document count and growth rate. The data highlights a strong focus on fly ash, GGBS and AA in material specific research, while other areas like K_2SiO_3 and KOH remain less explored.

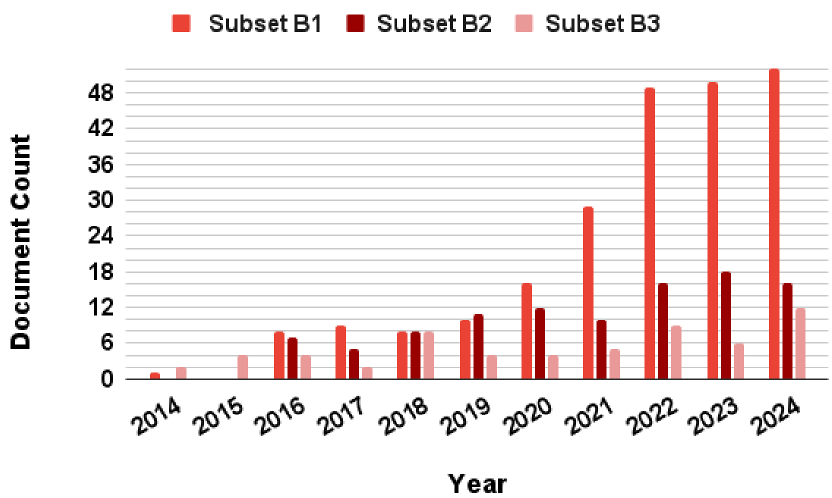


Fig. 8. Year-wise distribution of publications in Set B

Set B (Fig. 8), which consists of property specific data, shows a noticeable rise over the decade. The total number of documents grew from 3 in 2014 to 80 in 2024 across all subsets, reflecting a growth rate of approximately +39%. This indicates rapid and consistent expansion in document accumulation or production, reflecting a strong upward trend over the past 10 years.

- Subset B1 (Mechanical property: compressive strength, flexural strength, tensile strength, durability, thermal resistance) started with 1 document in 2014 and grew to 52 in 2024, with a total of 232 documents and a growth rate of +48.4%. This subset experienced a large increase after 2019, reflecting the overall increase.
- Subset B2 (Physical Properties: Density, Workability, Setting Time, Shrinkage) started with 0 documents and reached 16 for a total of 103 documents and had a growth rate of +32%.
- Subset B3 (Chemical Properties: Molarity, Curing, Temperature Curing, Ambient Curing, Alkalinity, Sulfate Attack) increased from 2 to 12 documents for a total of 60 documents and had a very high growth rate of +19.6%, which shows a significant and rapid focus in this research area.

While Subset B1 dominates in terms of document count and shows a notable spike after 2019, Subset B3 demonstrates the highest growth rate, reflecting increasing interest in chemical properties. Overall, Set B exhibits a strong upward trend, with all subsets contributing to the expansion.

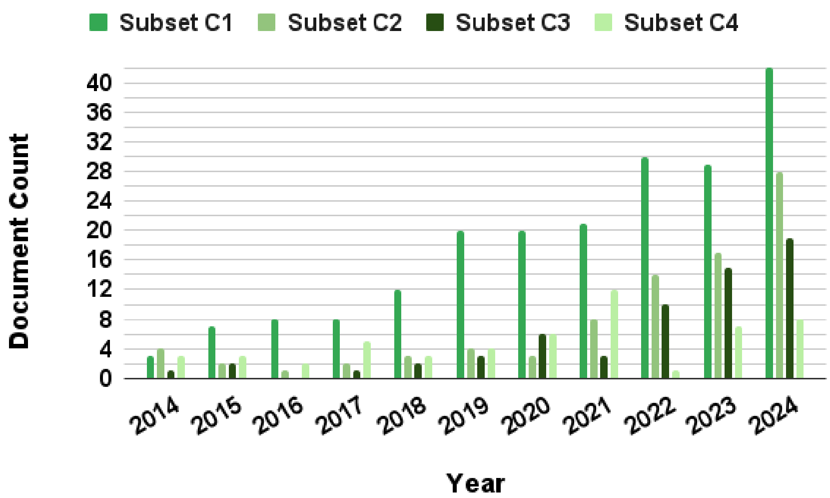


Fig. 9. Year-wise distribution of publications in Set C

Set C (Fig. 9), which consists of miscellaneous topics, shows a steady rise over the decade. Starting with 11 documents in 2014 across all subsets, the total number of documents have increased to 97 in 2024, reflecting a growth rate of approximately +24%.

- Subset C1 (Alternative Binders, Low Density Concrete, Precast Construction, Self-Compacting Concrete) increased from 3 documents in 2014 to 42 in 2024, for a total of 200 documents and a growth rate of +30.2%.
- Subset C2 (Research, Development, Performance, Production, Advancement, Adoption) increased from 4 to 28 documents for a total of 86 documents and a growth rate of +21.5%.
- Subset C3 (Sustainability, Green Building Materials, Waste Material Utilization, Carbon Footprint, Global Warming Impact) showed the most dramatic growth, starting from 1 document and reaching 19, for a total of 62 documents and a growth rate of +34.2%.
- Subset C4 (Industrial Applications, Repair and Rehabilitation, Production Techniques) increased from 3 to 8 documents, for a total of 54 documents and a growth rate of +10.3%.

While subset C1 leads in total documents, subset C3 shows the strongest growth rate, highlighting the growing focus of research on sustainability. Overall, set C has maintained a consistent upward trajectory, with all subsets showing positive expansion despite different growth rates.

Overall, a strong growth trend is evident across all research subgroups, with subgroup B1 showing the highest growth rate, indicating significant progress and interest in mechanical properties. The key influential areas include fly ash and GGBS in Set A, mechanical and chemical properties in Set

B, alternative binders and sustainability in Set C. The emerging focus should be on sustainability (C3) and advanced mechanical properties (B1), which show the most dynamic expansion.

3.3. Country-Wise Publication Details

To identify global hotspots and understand the geographical distribution of research contributions in detail, the country map is prepared using the Iipmaps tool, as illustrated in Fig. 10. A full counting method was applied, giving full credit to each country listed on each co-authored publication. From 120 countries seen globally, 11,078 documents related to GPC for the span 2014-2024 are obtained. Over the global landscape, the level of GPC research is demarcated using color grading. A color gradient is used to illustrate the intensity of research activity, with darker shades representing a higher document count. The highest publication volumes come from China, India, Australia, the US and Malaysia, ranked in descending order. China contributes 24.7% of the total publications in the GPC sector, with 2,736 documents marked in dark red. India follows with 18%, totaling 1,997 documents in red. Australia represents 8.5% with 940 documents in light red, while the United States accounts for 6.3% with 700 documents in light red. Malaysia contributes 6.2% with 692 documents.

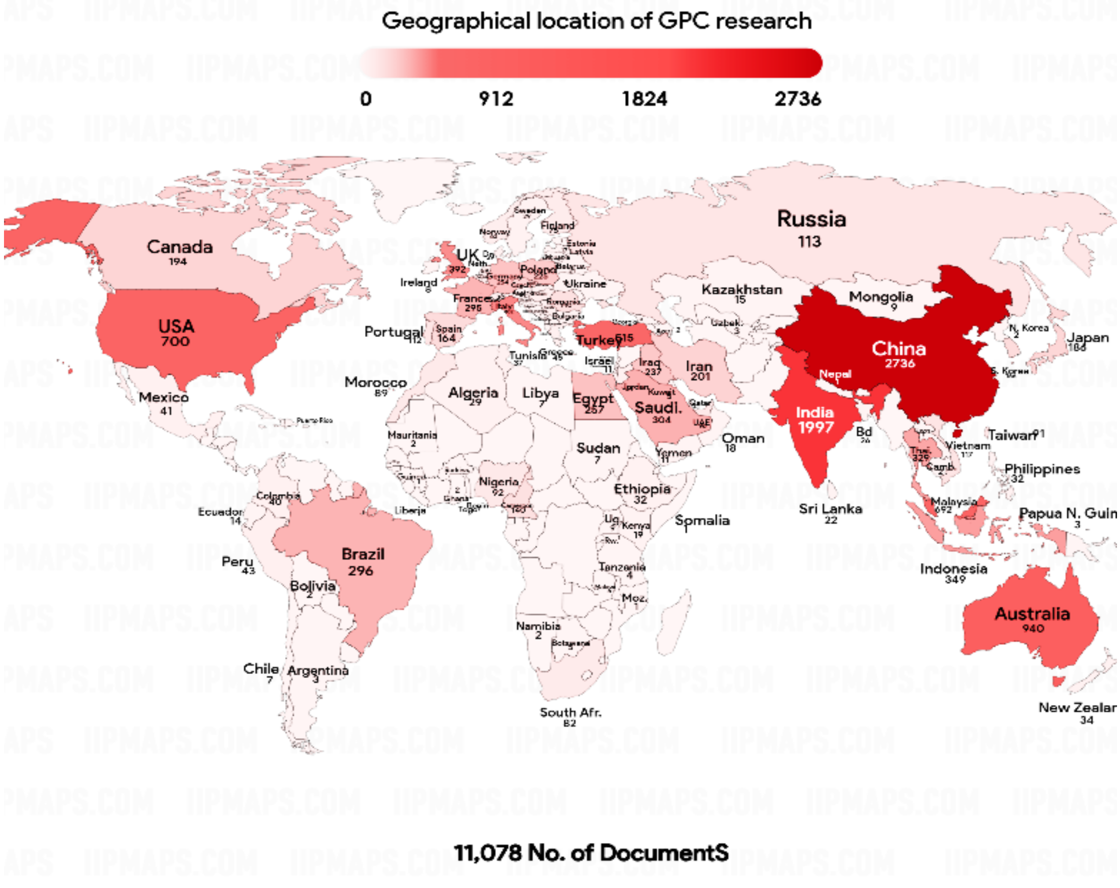


Fig. 10. Geographical spread of global GPC research

Table 3 presents a comprehensive analysis of research priorities and gaps in geopolymer technology across countries. The findings show a universal emphasis on compressive strength and curing techniques, underscoring their fundamental role in material development. China and the US demonstrate particular strengths in microstructural characterization using advanced techniques such as SEM. Significant research gaps remain in many important areas. Research into durability issues such as fire resistance (China), acid resistance (Malaysia) and corrosion protection (Malaysia) is still insufficient. Similarly, more attention needs to be paid to sustainable approaches, including recycled aggregates (USA) and life cycle assessment (USA). Innovative solutions such as fiber reinforcement (Australia), chemical bonding mechanisms (China) and efficiency enhancement (Malaysia) are also underrepresented. Regionally, India excels in fly ash and blast furnace slag applications, while Australia leads in slag utilization and tensile performance studies. Malaysia stands out for its work on sodium hydroxide activated systems. These findings show that while the core mechanical properties are well established, there are significant opportunities to strengthen research in durability, sustainability and material innovation. Addressing these gaps could significantly advance both the practical applications and environmental benefits of geopolymer technology.

Table 3. Top 5 country-wise dominant and underexplored research areas in geopolymer studies

Country	Quantitative		Qualitative	
	Dominant Topics	Underexplored Topics	Dominant Topics	Underexplored Topics
China	Compressive Strength, Metakaolin, Curing	NA	Microstructure	Ductility, Chemical Bonds, Basalt Fiber, Rheology, Fire Resistance
India	Fly Ash Compressive Strength, NaOH Activation, Blast Furnace Slag	Partial Replacement, Mix Designs	Inorganic Polymers	Polymer Concretes, Durability, Alkaline Activators
Australia	Compressive Strength, Slags, Curing, Tensile Strength, Silicates	Drying Shrinkage	NA	GGBS Optimization, Glass Fibers, Fiber Reinforced Polymer Composites, Experimental Validation
USA	Fly Ash, Compressive Strength, Curing	Recycled Aggregates, Kaolin	Inorganic Polymers, SEM	Portland Cement Blends, Polymerization, Life Cycle Analysis
Malaysia	Compressive Strength, NaOH, Silicates, Slags	NA	Geopolymer Concrete	Corrosion Resistance, Carbon based Geopolymers, Alkali activated Systems, Acid Resistance, Workability

National policies and environmental laws drive targeted research in major countries. China's five-year plans promote the use of blast furnace slag for low carbon development. Australia's Commonwealth Scientific and Industrial Research Organization’s (CSIRO) partnership with Heavy Industry Low Carbon Transition Cooperative Research Centre (HILT) supports metakaolin based binders for mining. The US Environment Protection Agency (EPA) regulates fly ash recycling under the Coal Combustion Residues Rule. Malaysia's green building certifications encourage palm oil fuel ash recycling. India's Ministry of Environment, Forest and Climate Change (MEF&CC) mandates 100% fly ash use, while its Smart Cities Mission and Indian Green Building Council (IGBC) certifications encourage sustainable materials and partnerships. These policies directly link industrial by-product availability and regulatory support to each country's leadership in geopolymer research. In India, these policies have directly encouraged research focused on the use of fly ash (aligned with coal power byproducts) and NaOH activated slag systems, prioritizing compressive strength as per Bureau of Indian Standards codes (BIS). However, critical gaps persist in tropical durability (monsoon/thermal effects), activator optimization (alternative/low molarity mixes) and field implementation (lack of IS codes/rural quality control). Addressing these could enhance practical adoption.

The dataset (Fig. 11) highlights China (a total of 2,736 papers) and India (1,997 papers) as the leaders in GPC research. While China has maintained its consistent dominance with 661 papers in 2024, India has shown notable growth, surpassing China twice in 2018 (128 vs. 87 papers) and in 2020 (217 vs. 205) and achieving the highest output in 2019 (186 papers). This growth reflects India's focus on sustainable construction, which is likely driven by educational investment and infrastructure demands. Meanwhile, Turkey emerged as a major player, rising from 6 documents in 2014 to 123 in 2024, while Australia, once the leader (110 documents in 2021), fell after 2022. The US rebounded after a mid-decade recession (24 documents in 2015) and reached 101 in 2024, while Malaysia, which was initially strong (71 documents in 2016), saw a decline in GPC research contribution after 2020.

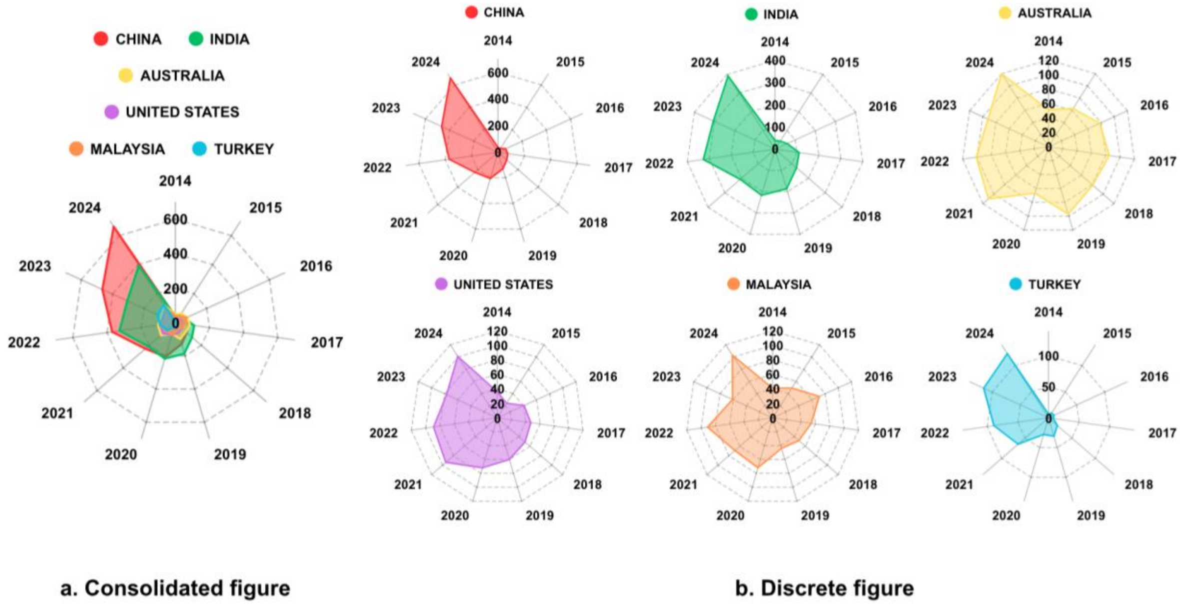


Fig. 11. Annual publication output of the six leading countries in geopolymer research

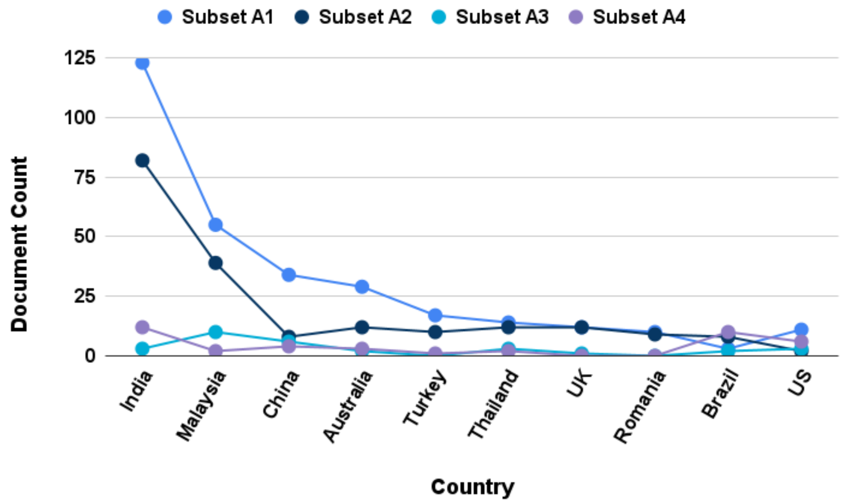


Fig. 12. Country-wise document distribution for Set A

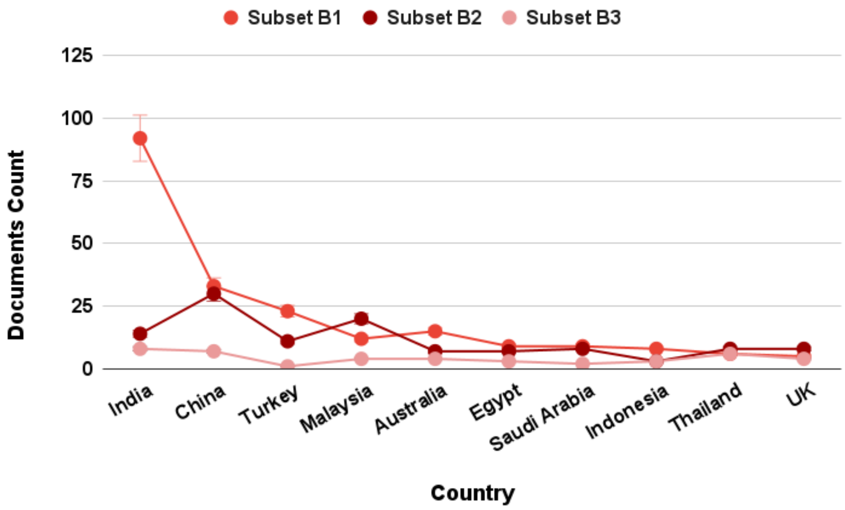


Fig. 13. Country-wise document distribution for Set B

India emerged as the leading contributor in the subset analysis, showing the highest publication rate among all the countries examined. Subset A1 has the highest number of documents across all years, indicating it is the most active area of research. In total, there are 640 documents overall and 220 from India, followed by Malaysia and China for set A (Fig. 12). Set A highlights the geographical distribution of research in GPC, with India and Malaysia dominating in fly ash, GGBS and sodium-based activators. While Subset A1 and A2 drive the majority of research, Subset A3 and A4 remain niche areas with contributions from countries like China, Brazil and the United States. This data underscores the global interest in sustainable construction materials, identifies key players and emerging trends in GPC research.

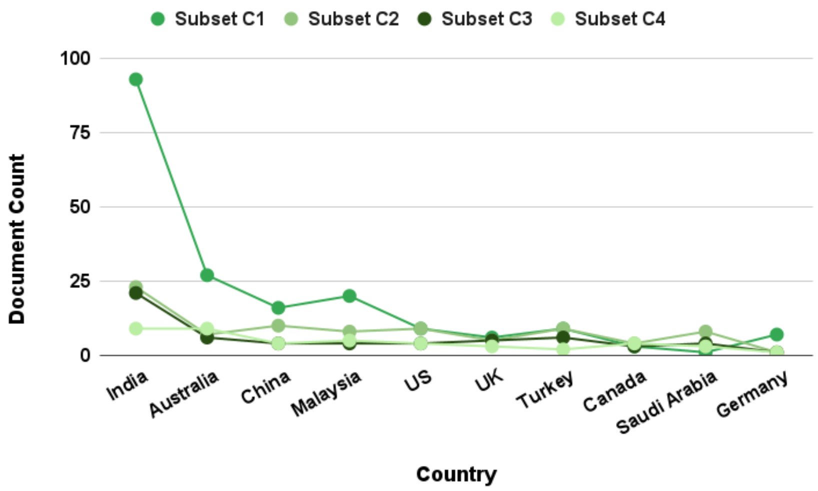


Fig. 14. Country-wise document distribution for Set C

Set B underlines documents published with India dominating in mechanical and chemical properties and China leading in physical properties. Set B has 114 counts from India, followed by China and Turkey. Where, in total, it has 401 documents (Fig. 13). While Subset B1 and B2 drive the majority of research, Subset B3 remains a less focused area in Chemical Properties, with contributions from countries like Thailand.

The Set C domain has a total of 146 publications in India and globally it's 397, followed by Australia and China, etc. (Fig. 14). Analysis of Set C in miscellaneous GPC topics, with India having the highest count in alternative binders, production and sustainability, Australia leading in low density concrete and industrial applications. While Subset C1 and C3 drive the majority of research, Subset C4 remains a niche area with contributions from countries like Malaysia.

3.4 Publications Based on Author Details

In the total 5174 papers obtained, this metric has focused on unique authorships of only first authors and allocated full authorship to the first author for the computation of the number of papers of top authors in the field. It is observed that a total of 161 unique first authors have contributed to the field through their research on GPC. The list of the top 10 global authors, for the last 10 year's span, is provided in descending order based on their number of publications in Fig. 15. However, co-authorship in these publications is not considered in this list. This list counts each author's publications separately, even if they worked together on the same paper. Therefore, if two authors co-author an article, the same article is counted once for each author.

Abdullah, M.M.A.B., from Malaysia, has published the maximum papers in the research of GPC. The effect of curing temperature on the physical and chemical properties of geopolymers was first published by Abdullah. M.M.A.B. in 2011. His topic of research in the years 2019–2023 includes compressive Strength, geopolymers and inorganic polymer. A 2025 study has investigated sustainable geopolymer adsorbents containing silica fume as a partial replacement for metakaolin for the removal of copper ions from synthetic solutions. Next, Chindaprasirt, Prinya (Thailand), having the first publication in 2006, has explored the area of Compressive Strength, Rice Husk Ash, Ultimate Tensile Strength, along with topics similar to Abdullah, M.M.A.B., from 2019 to 2023. Further, Sanjayan, Jay G. (Australia) has worked in areas like 3D Printing, Additive Manufacturing, along with Rheology in the years 2019-2023. Rossignol, S. (France) has worked in the areas of Compressive Strength, Phosphoric Acid, Inorganic Polymer, geopolymers and metakaolin in the span from 2019 to 2023. Lionelli, C. (Italy) has conducted research on geopolymer materials from 2008 to 2025, with primary focus areas including compressive strength, portland cement alternatives, sodium activated systems and inorganic polymers

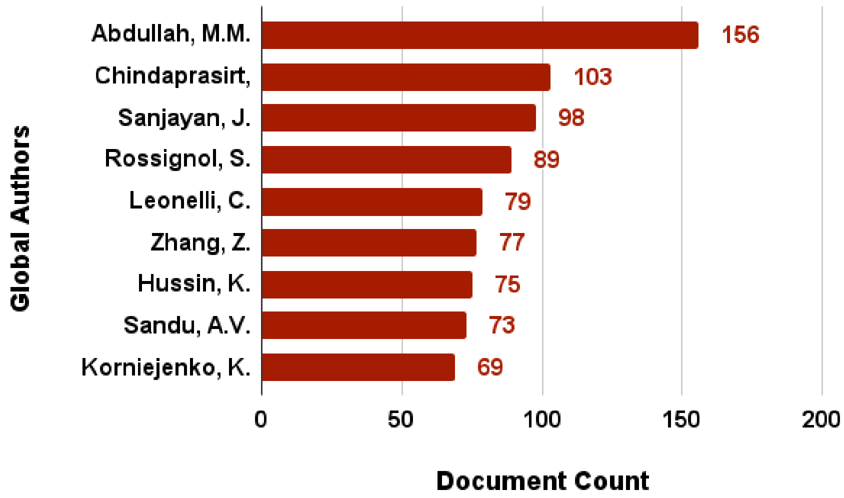


Fig. 15. Number of papers published by top 10 authors globally in geopolymer research

Table 4 shows the publication records of the top 10 geopolymer researchers globally. However, this unfiltered dataset includes all years of publication and does not distinguish the period 2014-2024. Sanjayan. J. (Australia) leads in citation impact (31,767), while Abdullah M.M.A.B. (Malaysia) dominates in publication volume (858 papers). Thailand's Chindaprasit P. achieves the second highest H-index (86), indicating a consistently high-quality product. European researchers show moderate but steady contributions, with France's Rossignol S. maintaining a strong h-index (52) despite fewer publications. The data shows diverse research strengths across geographical regions in the geopolymer field.

Table 4. Publication metrics of top 10 global geopolymer researchers

Author	Country	Documents	Citations	h-index
Abdullah, M.M.A.B.	Malaysia	858	13,539	53
Chindaprasirt, P.	Thailand	475	28,351	86
Sanjayan, J.	Australia	457	31,767	96
Rossignol, S.	France	248	8,279	52
Leonelli, C.	Italy	475	12,394	58
Zhang, Z.	China	247	18,871	78
Hussin, K.	Malaysia	375	8,675	45
Sandu, A.V.	Romania	459	5,650	36
Korniejenko, K.	Poland	144	2,237	26
Kamseu, E.	Cameroon (Africa)	178	5,446	44

Fig. 16 shows an analysis of the author collaboration network. The network demonstrates strong and diverse teamwork within structured Sets (A, B and C), with 141 authors forming 13 main research clusters. Notably, authors such as Horpibulsuk S, Chindaprasit P and Sanjayan J are central focal points due to their large number of publications and collaborations. The strongest partnership is between Arulraja A and Horpibulsuk S, who have co-written 11 times. The research groups focus on different topics, specifically on the properties, applications and component evaluation of GPC. Citations enable readers to search for referenced sources, while Table 5 systematically presents publication metrics for the ten most prolific authors of Set A, including their bibliographic details. Abdullah M. (23 papers in total) for Set A. Zhang P. For Set B (7 papers) (Table 6) and Sarker P.K. (5 papers) for Set C, have the highest number of publications in the domain of materials- fly ash, GGBS and alternative binders, low density concrete, precast construction with self compacting concrete globally.

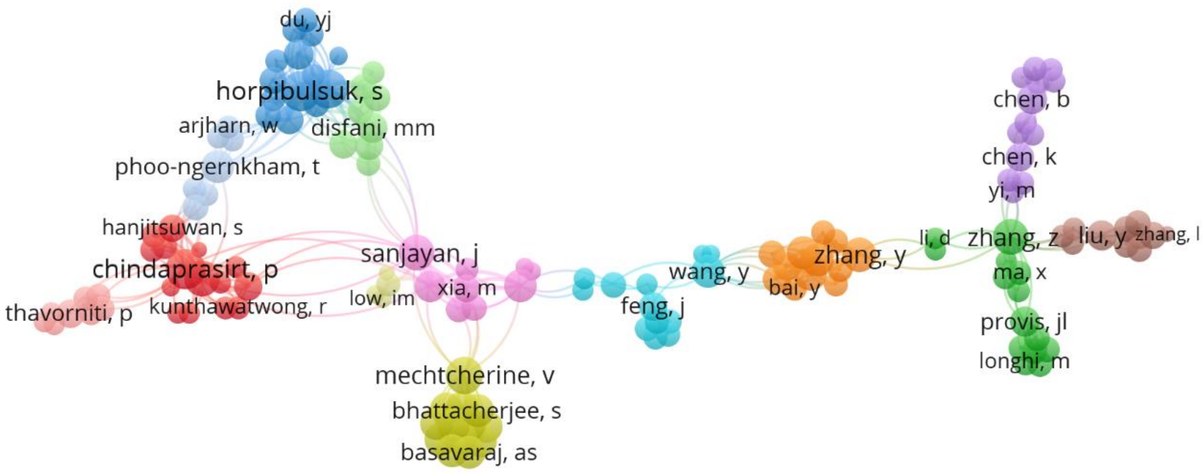


Fig. 16. Author collaboration network map for combined Sets A, B & C in geopolymer research

Table 5. List of top 10 authors for Set A, material-focused keywords in geopolymer research

Set A							
Subset A1		Subset A2		Subset A3		Subset A4	
Author	Count	Author	Count	Author	Count	Author	Count
Abdullah, M.	13	Abdullah, M.	10	Rossignol, S.	6	Gupta, R.	3
Hussin, K.	8	Hussin, K.	7	Basri, M.S.M.	2	Mashifana, T.	3
Zainal, F.F.	8	Zainal, F.F.	6	Bhardwaj, P.	2	Dias, D.P.	2
Arulrajah, A.	6	Abbass, M.	5	Gharzouni, A.	2	Haque, S.	2
Ekaputri, J.J.	6	Kamarudin, H.	5	Gupta, R.	2	Khalifeh, M.	2
Rahmat, A.	6	Sandu, A.V.	5	Ishak, M.R.	2	Omran, M.	2
Horpibulsuk, S.	5	Singh, G.	5	Joussein, E.	2	Panda, S.	2
Tahir, M.F.M.	5	Arulrajah, A.	4	Mazlan, N.	2	Panigrahi, S.K.	2
Al Bakri A, M.M.	4	Horpibulsuk, S.	4	Mishra, D.	2	Riella, H.G.	2
Alengaram, U.J.	4	Leonelli, C.	4	Mustapha, F.	2	Shaikh, F.	2

Table 6. List of top 10 authors for Set B, property-focused keywords in geopolymer research

Set B					
Subset B1		Subset B2		Subset B3	
Author	Count	Author	Count	Author	Count
Zhang, P.	7	L, Petr	5	Chavsuwan	3
Anand, N	6	A, Al Bakri	4	Dev, N.	3
Canpolat, O	5	B, Abdullah.	4	Verma, M.	3
Ahmed, H. U	4	Mucsi, G.	4	A, Al Bakri	2
Kanagaraj, B.	4	Ahmad, R.	3	Antoni	2
Khalil, W.I.	4	Alomayri, T.	3	Bourbigot, S.	2
M,A.Abdulkadir	4	B, K. Ewa	3	Davy, C.A.	2
Uysal, M.	4	Deng, Z.	3	Fontaine, G.	2
A, Al Bakri	3	Ercoli, R.	3	Hardjito, D.	2
Arunkumar, K.	3	Hussin, K.	3	Kittisayarm,	2

It is observed that altogether 166 documents were published in Set A (Table 5), made significant contributions in the field of Fly ash, GGBS and AA, where more research is needed in potassium-based activator. Similarly, from Set B (Table 6), 102 documents have fewer documents in physical properties- density, workability, setting time, as well as shrinkage, as compared to mechanical and chemical properties. From Set C (Table 7), 119 documents were recorded in the field of miscellaneous- alternative binder, low density concrete, precast construction and self-compacting concrete. Broad categories of research (development, performance, production, advancement and adoption), sustainability (green construction materials, waste material utilization, carbon footprint and global warming impact) and industrial applications (repair, rehabilitation and production techniques) have approximately similar search results.

Table 7. List of top 10 authors for Set C miscellaneous- focused keywords in geopolymer research

Set C							
Subset C1		Subset C2		Subset C3		Subset C4	
Author	Count	Author	Count	Author	Count	Author	Count
Anand, N.	10	Horpibulsuk, S.	3	Bahmani, H.	3	Ramli, M.	3
Kanagaraj, B.	9	Aldemir, A.	2	Mostofinejad, D.	3	Sanjayan, J.	3
Lubloy, E.	8	Arulrajah, A.	2	Al-Fakih, A.	2	Bagheri, A.	2
Panda, S.	6	Ashour, A.	2	Alengaram, U.J.	2	Ban, C.C.	2
Sarker, P.K.	5	Bahmani, H.	2	Habert, G.	2	De Belie, N.	2
Pradhan, P.	4	Danish, A.	2	Jeyalakshmi, R.	2	Ganesan, N.	2
Al Bakri A, M.M.	3	Daniyal, M.	2	Kaplan, G.	2	Gökçe, H.S.	2
Al-Ameri, R.	3	Ganachari, S.V.	2	Khennane, A.	2	He, P.	2
Ganeshan, M.	3	Li, W.	2	Mostafaei, H.	2	Jia, D.	2
Hussin, M.W.	3	Mostofinejad, D.	2	Nataraja, M.C.	2	Melchers, R.E.	2

3.5 Documents by Year, Authors and Funding Sources for India

India is actively contributing to the development and application of GPC through research, pilot projects and government policies. Research or activity in GPC has generally increased over the years, particularly from 2015 to 2024 (Fig. 17).

- Subset A1 (Fly ash, GGBS, AA) leads with the highest activity, peaking in 2024 (18 entries), driven by the sustainable use of fly ash and GGBS. Subset A2 (AA, NaOH, Na_2SiO_3) shows moderate activity, peaking in 2024 (8 entries), with stable trends. Subsets A3 (material, composition) and A4 (potassium-based AA) have low activity, indicating niche or underexplored areas.
- Subset B1 (Mechanical properties) is highly active, peaking in 2022 (23 entries), focusing on strength, durability and thermal resistance. Subsets B2 (Physical properties) and B3 (Chemical properties) show minimal activity, suggesting less prominence.
- Subset C1 (Innovative Applications) and C3 (Sustainability) are highly active, reflecting growing interest in sustainable and innovative uses.

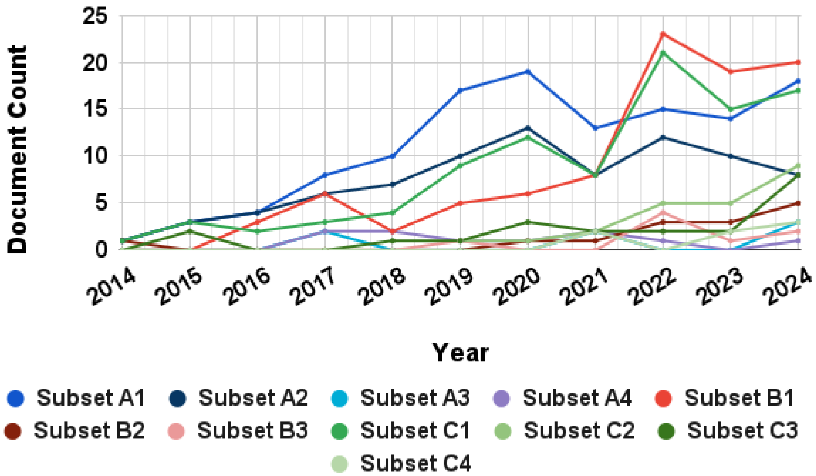


Fig. 17. Annual publication output of India for Sets A, B & C in geopolymer research

Subsets A3, A4, B3 and C4 (material composition, potassium-based a, chemical properties and industrial applications) have low activity, representing emerging areas with future potential. Overall, fly ash and GGBS based GPC dominate research, with a strong focus on mechanical properties and sustainability, while niche areas remain underexplored.

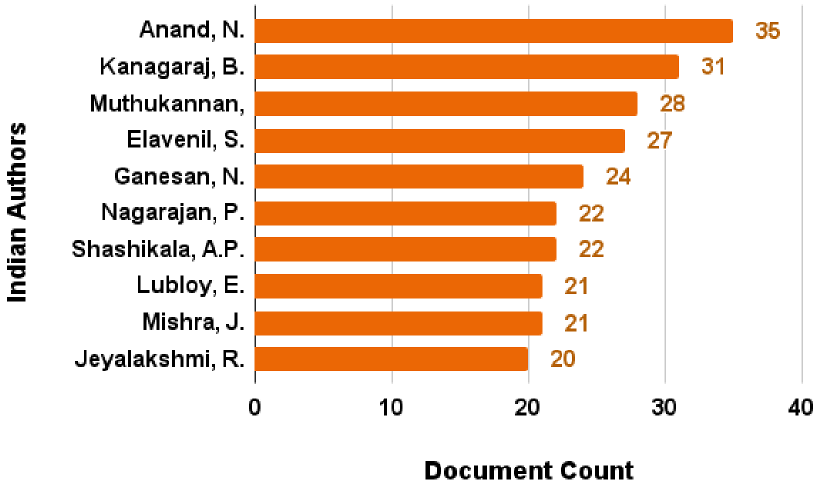


Fig. 18. Top 10 authors from India in geopolymer research

In Indian context, a cumulative total of 159 researchers are engaged in the scholarly investigation of geopolymer technology. The graphical representation in Fig. 18 elucidates the top ten researchers. Among the top three are, Anand N. having highest volume of published documents in durability, microstructural properties, as well as natural and recycled aggregates, followed by Kanagaraj B. publishing on GPC properties, strength, nanomaterials, lightweight geopolymer and precursor materials, Muthukannan researching on the structural performance, production of bricks, microstructure of ambient curing, as well as workability properties. In India, although there is active research on GPC, there are still significant opportunities to strengthen and expand research capacity. Enhancing interdisciplinary collaboration, improving experimental facilities, promoting large scale applications can further advance the understanding and use of GPC in the context of India. Table 8 summarizes the publication metrics of the top 10 geopolymer researchers in India.

Table 8. Publication metrics of top 10 Indian geopolymer researchers

Author	Citations	Documents	h-index
Anand, N.	2,075	145	28
Kanagaraj, B.	1,099	68	19
Muthukannan, M.	1,310	120	22
Elavenil, S.	961	89	18
Ganesan, N.	1,655	108	19
Nagarajan, P.	959	122	16
Shashikala, A.P.	897	75	15
Lubloy, E.	1,436	135	22
Mishra, J.	1,138	26	17
Jeyalakshmi, R.	978	79	15

Table 9 gives details of top authors in all three sets. Anand N. appears in both Set B and Set C with high counts (6 and 10, respectively), indicating significant contributions in both "Properties" and "Miscellaneous" categories. K. Balamural and A. Kadarkarai are prominent authors in both Set A and Set B, suggesting their work spans "Materials" and "Properties." Set C (Miscellaneous) has the highest counts, with A. Nammalvar, K. Balamural and P. Soumyaranjan as leading contributors. Some authors, like Verma, M. and Dev, N., appear multiple times across sets with varying counts, indicating their involvement in multiple areas.

Table 9. Top ten cited documents in India

SET A		SET B		SET C	
Author	Count	Author	Count	Author	Count
Jena, S.	4	Anand, N.	6	Anand, N.	10
Panigrahi, R.	4	K, Balamural	4	K, Balamural	9
Arunkumar, K.	3	Arunkumar, K	3	Panda, S.	6
Abbass, M.	5	Dev, N.	2	Pradhan, P.	4
Singh, G.	5	Najar, M.	2	Daniyal, M.	2
Bajpai, R.	2	Sakhare, V.	2	Ganachari, S.	2
Bhardwaj, P.	2	Verma, M.	2	Alengaram,U.	2
Gupta, R.	2	Dev, N.	3	Jeyalakshmi, R.	2
B. Karthiga.	1	Verma, M.	3	Ganesan, N.	2
Bawa, S.	1	Upreti, K.	2	Abraham, R.	1

Highlighting the relationship between financial support, research productivity and scientific impact, the role of funding in driving scientific innovation in research is critical. The National Natural Science Foundation of China is the highest sponsoring organization for all three sets: Set A, Set B & Set C. The analysis shows that Set B, which met all set criteria, has attracted the most funded projects. Primary funding sources include the Ministry of Science and Technology of China and the Natural Science Foundation of Henan Province. For Set A, top funding is from the Ministry of Higher Education, Malaysia and for Set C, the European Commission. Both Set A and Set C received funding from the Australian Research Council.

Bibliometric survey highlights the pivotal role of funding in driving innovation, with a strong correlation between financial support and impactful research outcomes. Technical challenges still hinder the widespread development and field use of GPC in the construction industry in India. In India, the leading sponsors are the All-India Council for Technical Education, the Department of Science and Technology, the Ministry of Science and Technology are the top funding sponsors.

4. Citation Analysis

In bibliometric reviews, citation analysis identifies influential works, maps research networks, assesses impact and detects trends, making them essential for data driven field analysis. The referenced literature supports this research and provides avenues for extended study. While examining internationally important papers (Table 10), we have specifically identified the most influential works from India in Table 11 through citation analysis. Singh B. (2015) and Hemalatha T. (2017) both papers appear in the top ten citation report with 1163 and 557 cited globally, as well as for India.

The synthesis and characterization of Geopolymer Foam Concrete (GFC) is investigated [29] using fly ash slag composite (class F) and a preformed foam mechanical mixing method. GFC exhibits superior sound absorption characteristics in comparison to conventional concrete. The research lacked sufficient data on GFC's long term benefits, particularly under varied environmental conditions. There is also limited insight into how different materials and their proportions affect GFC's properties.

The central part of this analysis [30] highlights how the structural properties of GPC show significant dependence on the molar concentration of the AAS. Through detailed Scanning Electron Microscopy (SEM) analysis, researchers observed that the incorporation of silica and nano-silica additives significantly improves the microstructure by enhancing particle packing density and interfacial bonding within the binder matrix, which directly contributes to superior mechanical performance. While the paper provides valuable theoretical insights into these material interactions and property enhancements, it notably omits discussion of practical implementations, lacking field applications or case studies that would demonstrate the real-world viability of GPC technology.

Table 10. Top ten cited documents globally

Document title	Authors	Source	Year	Citations
Geopolymer concrete: A review of some recent developments	Singh. B. Ishwarye.G. Gupto, M. Bhattacharove.S.K.	Construction and Building Materials	2015	1,163
Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition	Nath, P., Sarker, P.K.	Construction and Building Materials	2014	1,128
One-part alkali-activated materials: A review	Luukkonen, L, Abdollohnsied.Z. Yliniemi.J. Kinnunen. B Illikeinen. M.	Cement and Concrete Research	2018	987
Modification of phase evolution in alkali activated blast furnace slag by the incorporation of fly ash	Ismail, I. Bernal. S.A, Provis, J.L.... Hamdon S, Van Deventer. J.S),	Cement and Concrete Composites	2014	958
Fly ash based geopolymer: Clean production, properties and applications	Zhuang, X.Y. Chen, LKomarneni.S.... Yu, W.H. Wong, H.	Journal of Cleaner Production	2016	775
Geopolymers and other alkali activated materials: Why, how and what?	Provis, J.L.	Materials and Structures	2014	736
The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature	Deb.BS. Nath. B, Sarker, PK.	Materials and Design	2014	724
Geopolymer foam concrete: An emerging material for sustainable construction	Zhang.Z., Provis.IL, Reid, A, Wang, H.	Construction and Building Materials	2014	680
Clean production and properties of geopolymer concrete: A review	Amron, Y.H.M. Alrousef.R.Alobdulj obbor.H. El.Zeadani.M.	Journal of Cleaner Production	2020	606
A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete	Hemalatha T., Ramaswamy's.	Journal of Cleaner Production	2017	557

A research work [31] has assessed the incorporation of fiber in geopolymer composites serves a dual purpose, enhancing mechanical performance while reducing quasi brittle behavior, resulting in improved toughness and ductility characteristics. However, this reinforcement approach introduces microstructural changes, notably increased porosity, consequently elevating water absorption capacity. Current research reveals a significant knowledge gap regarding standardized testing protocols specifically developed for fiber reinforced geopolymers, creating challenges in comparative performance evaluation and quality control.

Another research [32] presents a systematic evaluation of how three commercial superplasticizers – naphthalene formaldehyde condensate (SNF), melamine based (SMF) and polycarboxylate ether (PCE), influence the performance and compressive strength characteristics of fly ash based geopolymer binders. Employing a standardized 1% dosage (by mass of fly ash), the investigation utilizes mini slump tests to quantitatively assess flowability improvements compared to control mixtures without superplasticizers. The findings address a significant gap in the literature by correlating workability enhancements with mechanical performance outcomes, offering practical guidance for geopolymer mix design optimization.

Findings from research [33] have demonstrated the feasibility of using construction and demolition waste derived Recycled Aggregates (RA) in GPC, while addressing key challenges in their implementation. The inherent porosity of RA results in significantly higher water absorption compared to natural aggregates, which needs presoaking of the aggregates. However, the paper identifies substantial variability in workability performance, underscoring the need for both standardized testing protocols to evaluate RA effects consistently and further research to better understand the relationship between aggregate absorption characteristics and fresh concrete behavior.

One of the studies establishes an integrated framework for geopolymer 3D printing, examining material composition, rheological behavior and printing parameters. Industrial by-products with optimal aluminosilicate content are selected, while precise ratio adjustment controls the setting properties. Rheological analysis ensures proper extrusion, complemented by nozzle design optimization. This process uses layered deposition, in which chemical kinetics and mechanical performance are rigorously evaluated to verify structural feasibility. Existing studies ignore the effects on raw material mixing and nozzle design, which limits optimization. There is a lack of innovation in geopolymer adaptation. An in-depth analysis of interlayer strength is required to enhance the 3D-printed structure's performance [34].

Yet another study uses the Taguchi method to efficiently optimize geopolymer mix designs, evaluating four important parameters: binder content (six levels), alkaline concentration (three levels), SS/SH ratio and A/B ratio. The sustainable formulation includes red mud with RHA, GGBS and recycled sand, demonstrating effective waste assessment and emission reduction. The experimental results identify the optimal composition [60% Rice Husk Ash (RHA), 20% GGBS, 20% red mud] through compressive strength and water absorption testing, supported by statistical [Analysis of Variance (ANOVA)] and microscopic analysis. However, the research presents significant limitations, including uninvestigated curing/environmental factors, absent long term durability assessments, a lack of comparative analysis with conventional materials and includes untested geographic utilities, all of which are critical for comprehensive performance evaluation and practical implementation [35].

A research work by Nazar [36] evaluates three AI techniques [Gene Expression Programming (GEP), Adaptive Neuro Fuzzy Inference System (ANFIS) and ANN Artificial Neural Networks (ANN)] to predict the compressive strength (245 data points) and slump (108 data points) of fly ash-based GPC. The GEP model shows superior performance, generating simpler, more reliable results through physical process-based relationships. Sensitivity analysis identifies key input parameters (water content, Al/FA ratio) that significantly affect the predictions. Seven statistical metrics [Relative Standard Error (RSE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Nash Sutcliffe Efficiency (NSE), RRMSE Relative Root Mean Square Error (RRMSE), Correlation Coefficient (R) and Coefficient of Determination(R^2)] have confirmed the accuracy of the model, with trends consistent with established literature. Developing optimal geopolymer mixtures remains complex and resource intensive, with barriers to practical implementation remaining despite AI advances. Fly ash variability leads to property discrepancies that models cannot fully capture. Additionally, the limited slump dataset (108 points versus 245 for strength) may compromise prediction reliability, underscoring the need for expanded data collection.

A review document [37] demonstrates that industrial wastes (biomass ash, red mud, recycled glass, heavy metals) can effectively replace conventional materials in geopolymer production, offering environmental benefits while addressing waste disposal challenges. While ambient curing is possible, heat curing at 60°C for 24 hours yields superior properties. However, the economic viability remains unclear, as the review lacks a full cost analysis of fly ash based geopolymer production, particularly regarding high molarity NaOH solutions and overall process economics.

Another investigation [38] examines the properties of Self Compacting GPC (SCGPC) cured at ambient temperature. The results show that controlled GGBFS concrete significantly increases compressive strength regardless of the curing period. While increased NaOH concentration has been found to enhance strength development, it concurrently reduces the mixture's fluidity. These findings highlight the need for an optimized balance between mechanical properties and workability in SCGC formulations. Furthermore, the research suggests that a comprehensive cost benefit analysis would be valuable for assessing the practical implementation of SCGC in construction applications.

Table 11. Top ten cited documents in India

Document title	Authors	Source	Year	Citations
Geopolymer concrete: A review of some recent developments	Singh, B., Ishwarya, G., Gupta, M., Bhattacharyya, S.K.	Construction and Building Materials	2015	1,163
A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete	Hemalatha, T. Ramaswamy, A	Journal of Cleaner Production	2017	557
Geopolymers as an alternative to Portland cement: An overview	Singh, N.B., Middendorf, B.	Construction and Building Materials	2020	454
Use of geopolymer concrete for a cleaner and sustainable environment – A review of mechanical properties and microstructure	Hassan, A., Arif, M. Sharig, M.	Journal of Cleaner Production	2019	425
Environmental impact assessment of fly ash and silica fume based geopolymer concrete	Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K.S., Singh, M	Journal of Cleaner Production	2020	382
Fly ash based ecofriendly geopolymer concrete: A critical review of the long term durability properties	Amran, M., Debbarma, S., Ozbakkaloglu. T.	Construction and Building Materials	2021	334
Effect of nano silica on the strength and durability of fly ash based geopolymer mortar	Adak, D., Sarkar, M., Mandal, S.	Construction and Building Materials	2014	312
A mix design procedure for geopolymer concrete with fly ash	Pavithra, P., Srinivasula Reddy, M., Dinakar, P., Satpathy, B.K., Mohanty, A.N.	Journal of Cleaner Production	2016	303
A critical review of geopolymer properties for structural fire resistance applications	Lahoti, M., Tan, K.H., Yang, E.-H.	Construction and Building Materials	2019	300
Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag	Saha, S., Rajasekaran, C.	Construction and Building Materials	2017	277

5. Summary and Discussion

In order to provide high quality concrete, reaching all standard parameters, satisfying the economic aspect, more research and limiting factors have to be studied, to meet sustainability, performance goals and economic requirements. This bibliometric survey highlights the rapid growth and diversification of GPC research over the past decade, underscoring its potential as an alternative to OPC. The analysis reveals that while global contributions are led by China and India, each country emphasizes different aspects ranging from material development to durability studies, reflecting varied industrial priorities and environmental policies. The findings also show that mechanical and chemical properties remain dominant research themes, while areas such as long-term performance, industrial scale adoption and economic feasibility remain underexplored. Despite significant progress, the absence of standardized codes, variability in mix design and limited field applications continue to restrict implementation due to lacking universally accepted codes, standards for design, production and application.

Future research should therefore focus on bridging laboratory findings with industrial practices, developing design standards and exploring cost effective systems. As a result, in the future, one may consider using various parameters, like molarity, workability, durability, fly ash to solution ratios, water to solution ratio, properties like resistance to acid attack, self-healing and curing options to minimize the stereotypical use of conventional concrete. This study is constrained to bibliometric analysis on the Scopus search engine only. In the future, one can refer to the study of the Web of Science, adoption of GPC with new emerging techniques, cost analysis, standardization challenges, long term performance and scaling up production. By addressing these gaps, GPC can transition from an experimental material to a mainstream solution that significantly reduces the construction industry's carbon footprint while advancing global sustainability goals.

5.1 Future Research

Future research on GPC should prioritize three key areas to enable widespread adoption, first, a mix design to standardize mechanical and durability performance optimization is required; second, long term durability studies under various environmental conditions are necessary to predict service life and third, comprehensive cost reduction and scaling strategies crucial for economic viability require to be studied. To ensure practical adoption, it is important to establish universal codes, standards and efforts should also be made to develop supporting policies to overcome industry resistance. Coordinated action on these fronts is crucial for making GPC a sustainable mainstream construction material.

Acknowledgement

The authors wish to thank the Department of Civil Engineering, Symbiosis Institute of Technology (SIT), Pune, India, for playing a crucial role in facilitating this research and are deeply grateful to Pune Construction Engineering Research Foundation (PCERF), Pune, India for their technical guidance and encouragement, which has significantly enriched the quality of this work.

References

[1] Davidovits J. Global warming impact on the cement and aggregates industries [Internet]. 1994 [cited 2025 Sep 21]. Available from: https://www.researchgate.net/publication/236503901

[2] Cozzi L. International Energy Agency. CO_2 total emissions by region 2000–2024 [Internet]. 2025 Mar [cited 2025 Sep 21]. Available from: https://www.iea.org/data-and-statistics/charts/co2-total-emissions-by-region-2000-2024

[3] Tiseo I. Global and India cement CO_2 emissions 1960–2023 [Internet]. Statista; 2025 [cited 2025 Feb 21]. Available from: https://www.statista.com/statistics/1091672/carbon-dioxide-emissions-global-cement-manufacturing/

[4] Jaganmohan M. Carbon dioxide emissions from the manufacture of cement in India from 1960 to 2023 [Internet]. Statista; 2025 [cited 2025 Sep 21]. Available from: https://www.statista.com/statistics/1198693/carbon-dioxide-emissions-cement-manufacturing-china/

[5] Davidovits J. Properties of geopolymer concrete. In: Conference on Alkali Cements and Concretes [Internet]. 1994 [cited 2024 Dec 27]. p. 131–49. Available from: https://www.geopolymer.org

[6] Rangan BV. Geopolymer concrete for environmental protection. Indian Concrete J [Internet]. 2014 [cited 2025 Jan 5]; Available from: https://www.researchgate.net/publication/286116300

[7] Davidovits J. Geopolymeric concretes for environmental protection [Internet]. 1990 [cited 2025 Jan 5]. Available from: https://www.researchgate.net/publication/292545984

[8] Provis JL, Palomo A, Shi C. Advances in understanding alkali-activated materials [Internet]. Cem Concr Res. 2015 [cited 2025 Mar 11]. Available from: https://doi.org/10.1016/j.cemconres.2015.04.013

[9] Hadi MN, Al-Azzawi MSA, Yu T. Effects of fly ash characteristics and alkaline activator components on compressive strength of fly ash-based geopolymer mortar [Internet]. Available from: https://ro.uow.edu.au/eispapers1

[10] Goriparthi MR, Gunneswara Rao TD. Effect of fly ash and GGBS combination on mechanical and durability properties of GPC. Adv Concr Constr. 2017;5(4):313–30. https://doi.org/10.12989/acc.2017.5.4.313

[11] Kanagaraj B, Lubloy E, Anand N, Hlavicka V, Kiran T. Investigation of physical, chemical, mechanical and microstructural properties of cement-less concrete: State-of-the-art review [Internet]. 2022 [cited 2025 Jan 15]. Available from: http://creativecommons.org/licenses/by/4.0/

[12] Imtiaz L, Ur Rehman SK, Memon SA, Khan MK, Javed MF. A review of recent developments and advances in eco-friendly geopolymer concrete. Appl Sci (Switzerland). 2020;10(21):7838. https://www.mdpi.com/2076-3417/10/21/7838
[13] Amran M, Al-Fakih A, Chu SH, Fediuk R, Haruna S, Azevedo A, et al. Long-term durability properties of geopolymer concrete: An in-depth review. Case Stud Constr Mater. 2021;15:e00661. https://doi.org/10.1016/j.cscm.2021.e00661
[14] Davidovits J. Geopolymer chemistry and sustainable development [Internet]. 2005 [cited 2025 Jan 8]. Available from: https://www.researchgate.net/publication/284514069
[15] Rangan BV. Geopolymer concrete for environmental protection. Indian Concrete J [Internet]. 2014 [cited 2025 Jan 5]. Available from: https://www.researchgate.net/publication/286116300
[16] Singh NB, Middendorf B. Geopolymers as an alternative to Portland cement: An overview. Constr Build Mater. 2020;237:117455. https://doi.org/10.1016/j.conbuildmat.2019.117455
[17] Mustafa Al Bakri AM, Kamarudin H, Khairul Nizar I, Bnhussain M, Zarina Y, Rafiza AR. Correlation between Na_2SiO_3/NaOH ratio and fly ash/alkaline activator ratio to the strength of geopolymer. Adv Mater Res. 2012;341–2:189–93. https://doi.org/10.4028/www.scientific.net/AMR.341-342.189
[18] Dai X, Aydin S, Yardimci MY, De Schutter G. Rheology and structural build-up of sodium silicate- and sodium hydroxide-activated GGBFS mixtures. Cem Concr Compos. 2022;131:104570. https://doi.org/10.1016/j.cemconcomp.2022.104570
[19] Hardjito D, Rangan BV. Development and properties of low-calcium fly ash-based geopolymer concrete [Internet]. 2005 [cited 2025 Jan 5]. Available from: https://www.researchgate.net/publication/228794879
[20] Wallah SE, Rangan BV. Low-calcium fly ash-based geopolymer concrete: Long-term properties [Internet]. 2006 [cited 2025 Jan 5]. Available from: https://www.geopolymer.org/wp-content/uploads/curtin_flyash_GC-2.pdf
[21] Lloyd NA, Rangan BV. Geopolymer concrete with fly ash [Internet]. 2010 [cited 2025 Jan 5]. Available from: http://www.claisse.info/Proceedings.htm
[22] Islam A, Alengaram UJ, Jumaat MZ, Bashar II. Development of compressive strength of GGBFS–palm oil fuel ash–fly ash-based geopolymer mortar. Mater Des. 2014;56:833–41. https://doi.org/10.1016/j.matdes.2013.11.080
[23] Kumar S, Kumar R, Mehrotra SP. Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash-based geopolymer. J Mater Sci. 2010;45(3):607–15. https://doi.org/10.1007/s10853-009-3934-5
[24] Allahverdi A, Najafi E. Effects of blast-furnace slag on natural pozzolan-based geopolymer cement. Ceramics Silikáty. 2011: 55 (1) 68-78. https://www.researchgate.net/publication/268343898
[25] Nath P, Sarker PK. Geopolymer concrete for ambient curing condition [Internet]. Available from: https://www.researchgate.net/publication/266222256
[26] Davidovits J. Geopolymer cement [Internet]. 2013 [cited 2025 Jan 5]. Available from: https://www.geopolymer.org
[27] Ahmed HU, Mohammed AA, Rafiq S, Mohammed AS, Mosavi A, Sor NH, Qaidi SMA. Compressive strength of sustainable geopolymer concrete composites: A state-of-the-art review. Sustainability (Switzerland). 2021;13(24):13502. https://doi.org/10.3390/su132413502
[28] Scopus [Internet]. [cited 2025 Jan 10]. Available from: https://surl.lu/lkjmqr
[29] Zhang Z, Provis JL, Reid A, Wang H. Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete. Cem Concr Compos. 2015;62:97–105. https://doi.org/10.1016/j.cemconcomp.2015.03.013
[30] Shilar FA, Ganachari SV, Patil VB, Khan TMY, Dawood Abdul Khadar S. Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: A review. Case Stud Constr Mater. 2022;16:e01014. https://doi.org/10.1016/j.cscm.2022.e01014
[31] Ranjbar N, Zhang M. Fiber-reinforced geopolymer composites: A review. Compos Part B Eng [Internet]. 2019 . https://doi.org/10.1016/j.cemconcomp.2019.103498
[32] Nematollahi B, Sanjayan J. Effect of different superplasticizers and activator combinations on workability and strength of fly ash-based geopolymer. Mater Des. 2014;57:667–72. https://doi.org/10.1016/j.matdes.2014.01.064
[33] Thomas BS, Yang J, Bahurudeen A, Chinnu SN, Abdalla JA, Hawileh RA, Hamada HM. Geopolymer concrete incorporating recycled aggregates: A comprehensive review. Cleaner Mater. 2022;3:100056. https://doi.org/10.1016/j.clema.2022.100056
[34] Chen K, Liu Q, Chen B, Zhang S, Ferrara L, Li W. Effect of raw materials on the performance of 3D printing geopolymer: A review. J Build Eng. 2024;84:108501. https://doi.org/10.1016/j.jobe.2024.108501
[35] Haq MZU, Sood H, Kumar R, Merta I. Taguchi-optimized triple-aluminosilicate geopolymer bricks with recycled sand: A sustainable construction solution. Case Stud Constr Mater. 2024;20:e02780. https://doi.org/10.1016/j.cscm.2023.e02780

[36] Nazar S, Yang J, Amin MN, Khan K, Ashraf M, Aslam F, et al. Machine learning interpretable-prediction models to evaluate the slump and strength of fly ash-based geopolymer. J Mater Res Technol. 2023;24:100–24. https://doi.org/10.1016/j.jmrt.2023.02.180

[37] Toniolo N, Boccaccini AR. Fly ash-based geopolymers containing added silicate waste: A review. Ceram Int. 2017;43(17):14545–51. https://doi.org/10.1016/j.ceramint.2017.07.221

[38] Partha M, Deb S, Sarathi P, Order D, Pradip D, Prabir N, et al. Effects of GGBFS blending with fly ash and activator content on workability and strength of geopolymer concrete cured at ambient temperature [Internet]. Available from: https://www.scirp.org/reference/referencespapers?referenceid=1885633