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The Role of Steel Slag Powder in Enhancing Concrete Strength: A Bibliometric and AI-Based Analysis of Research Trends

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A B S T R A C T

Steel slag powder (SSP) is gaining attention as an effective supplementary cementitious material in concrete, offering improved mechanical performance and promoting sustainable construction. This study conducts a bibliometric analysis of global research on SSP in concrete, with a specific focus on its role in enhancing compressive strength. A total of 836 articles published between 2000 and April 2025 were analyzed using VOSviewer and related tools to map key research patterns, including co-authorship networks, keyword co-occurrence, and institutional productivity. The analysis highlights the primary applications of SSP, notably in cement replacement, durability improvement, and environmental impact reduction. Influential countries, institutions, and authors are identified, alongside trending themes such as green concrete, industrial waste utilization, and microstructural engineering. Beyond bibliometric mapping, the study incorporates artificial intelligence (AI) tools especially machine learning (ML) and artificial neural networks (ANNs)which are increasingly employed to model and predict the performance of SSP-based concrete. These AI approaches aid in mixture optimization, strength prediction, and long-term durability assessments. Key challenges include the lack of standardized practices, variability in slag composition, and the scalability of SSP in large-scale applications. The study also suggests future directions such as multi-objective optimization, AI-based mix design systems, and enhanced interdisciplinary research. By offering a data-driven overview of current trends and technological integration, this research provides valuable insights for engineers, academics, and policymakers, highlighting the synergy between SSP innovation and AI in advancing sustainable concrete technologies.

1. Introduction

Concrete is the most widely used construction material in the world, owing to its versatility, strength, and durability[1], [2]. However, the increasing global demand for infrastructure, combined with the environmental concerns associated with the production of ordinary Portland cement (OPC), has driven researchers to explore sustainable alternatives[3], [4]. Among the various supplementary cementitious materials (SCMs) investigated, steel slag powder (SSP) has garnered significant attention due to its dual role in enhancing concrete performance and mitigating industrial waste. Steel slag, a by-product of the steel manufacturing process, is rich in calcium, silicon, and iron oxides, which contribute to its latent hydraulic and pozzolanic activity. When finely ground and incorporated into cementitious systems, SSP improves the mechanical properties of concrete particularly compressive strength while also promoting environmental sustainability through the reduction of cement consumption and carbon dioxide emissions[5], [6].

The integration of SSP into concrete not only addresses the challenges of waste management in the steel industry but also offers technical benefits such as improved durability, reduced permeability, enhanced resistance to sulfate attack, and long-term strength gain[7], [8]. These properties make SSP an ideal candidate for eco-friendly construction materials, especially in the context of green building initiatives and sustainable infrastructure development[8], [9]. Despite its potential, the widespread adoption of SSP-modified concrete faces several challenges, including variability in slag composition, limited understanding of its long-term behavior, and lack of standardized guidelines for its use in structural applications. Moreover, the influence of various parameters such as slag fineness, replacement ratio, chemical composition, and curing conditions on concrete performance introduces complexity that is difficult to capture using conventional empirical approaches[8], [9].

In recent years, the rapid advancement of artificial intelligence (AI) and machine learning (ML) techniques has opened new avenues for material modeling and performance prediction[10]–[12]. Unlike traditional statistical models, ML algorithms can analyze large and complex datasets, capture non-linear relationships among multiple variables, and provide accurate predictions without relying solely on experimental testing[13]–[15]. Techniques such as artificial neural networks (ANNs), support vector machines (SVMs), decision trees, and ensemble learning methods have been increasingly employed in concrete research to forecast compressive strength, optimize mix proportions, and assess durability indicators. When applied to SSP-modified concrete, these intelligent systems can offer significant insights into the effects of material composition and environmental factors on mechanical behavior, thus facilitating the design of more efficient and high-performance concrete mixes.[16]–[19]

Alongside technological advancements, the volume of academic literature on SSP in concrete has grown considerably over the past two decades. However, the diversity of research outputs ranging from laboratory studies to computational modeling has created a fragmented knowledge base[20]. To systematically capture the evolution of this research area, bibliometric analysis has emerged as a powerful tool. By quantitatively analyzing publication trends, author collaborations, keyword distributions, and citation networks, bibliometric studies provide a structured overview of scientific progress and identify influential contributors, emerging themes, and research gaps. When combined with AI applications, bibliometric analysis can not only map the state of the art but also reveal intersections between material innovation and computational intelligence[20], [21].

This study aims to conduct a comprehensive bibliometric and AI-based analysis of global research on the use of steel slag powder in concrete, with a specific emphasis on its impact on compressive strength. Using data extracted from the Scopus database and processed through VOSviewer, the research visualizes trends in publication activity, thematic development, and institutional collaboration from 2000 to April 2025. Furthermore, the study examines how AI and ML techniques have been integrated into the modeling and optimization of SSP-based concrete, exploring their potential to overcome existing limitations in empirical research.

2. Methodology

This study aims to analyze research on the role of steel slag powder (SSP) in enhancing concrete strength through a bibliometric and AI-based approach. It highlights key research trends, existing gaps, influential sources, leading institutions, notable authors, and contributing countries in the field. The study also seeks to provide strategic insights that will guide future research and improve the application of SSP in concrete materials. The methodology is structured into three main stages: data collection and selection, identification of appropriate scientific mapping techniques, and application of bibliometric analysis alongside artificial intelligence (AI) methods to uncover significant patterns and relationships within the research landscape.

2.1. Bibliometric Analysis

This review examines "The Role of Steel Slag Powder in Enhancing Concrete Strength: A Bibliometric and AI-Based Analysis of Research Trends" from 2000 to 2025. The bibliometric analysis method was employed to achieve this objective. Additionally, the study follows the PRISMA framework[22], [23], as illustrated in Fig. 1. Bibliometric analysis involves tracking research publications on a specific topic and extracting valuable insights by evaluating these studies across various parameters. The search in the Scopus database was conducted across multiple fields, including Title, Abstract, Author Keywords, and Keywords Plus, to ensure a comprehensive identification of relevant publications.

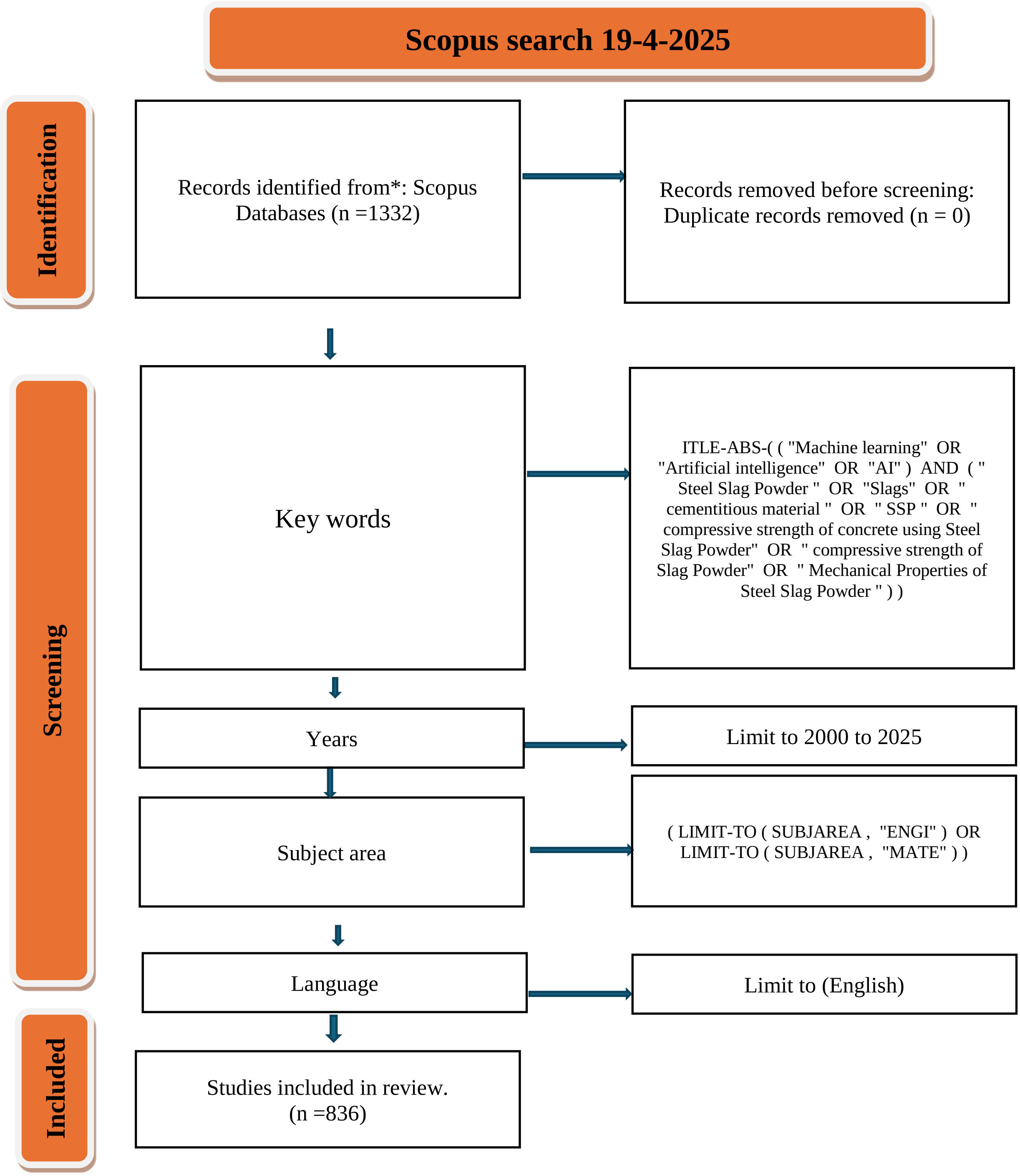

Fig. 1: PRISMA Framework for Bibliometric and AI-Based Analysis of Steel Slag Powder in Concrete Strength Enhancement.

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3. Results

Bibliometric analysis is a statistical approach used to quantify and evaluate the emerging trends within a particular field of study[22]–[25]. Bibliometric analysis has been applied to evaluate academic outputs across multiple disciplines[26], [27]. The search, conducted on the Scopus database from 2000 to 2025, utilized various search fields such as Author keywords, Title, Abstract, Author, and Keywords Plus. The search employed a combination of keywords using AND/OR logic, including terms like (("Machine learning" OR "Artificial intelligence" OR "AI") AND (" Steel Slag Powder " OR "Slags" OR " cementitious material " OR " SSP " OR " compressive strength of concrete using Steel Slag Powder" OR " compressive strength of Slag Powder" OR " Mechanical Properties of Steel Slag Powder ")) . The results were assessed based on titles and abstracts to ensure coherence with the article's theme and core topic.

The analysis utilized Scopus analysis and VOS viewer for data visualization. Graphs were generated using Microsoft Excel. Various details were extracted for each document, including (1) the number of documents per year, (2) average citations of articles per year, (3) author keywords and frequently used words in titles, (4) journals of publication for each article, (5) science categories, (6) most cited articles, (7) authors and coauthors for each article, (8) H-index for top 10 authors, (9) affiliation details for authors and coauthors, (10) countries of the authors, and (11) H-index for top 10 journals. Bibliographic maps were generated using VOS viewer software, encompassing keywords co-occurrence, countries co-authorship maps, and bibliographic coupling for countries and affiliations.

1332 documents were initially identified, with 836 aligning with the study's theme. These documents were then categorized as follows: 1598 research articles, 29 review papers, 124 conference papers, and 54 documents falling into other categories as shown in **Fig.4**. The dataset comprises 144 sources and 1723 keywords. The publications obtained showed an average growth rate of 43.60% per year. The most notable increase was observed between 2020 and 2024, reaching its peak with 687 publications in 2024, as shown in Fig. 2. The average annual citation was 50.80%, reported in 2024, as illustrated in Fig. 3. Only 15647 articles were cited for that particular year. Fig. 3 illustrates the fluctuation of journals over the years. Until 2024, the journal "Construction and Building Materials" held the top position, but it was surpassed by the "Materials," which accumulated a total of 30,704 articles. In terms of the Cite Score (2023) of journals, the "Journal of Cleaner Production" led the rankings with a score of 20.4, followed by " Construction and Building Materials " and " Journal of Building Engineering " with scores of 13.8 and 10.0, respectively, as shown in **Fig.5**, and as detailed in **Table 1**.

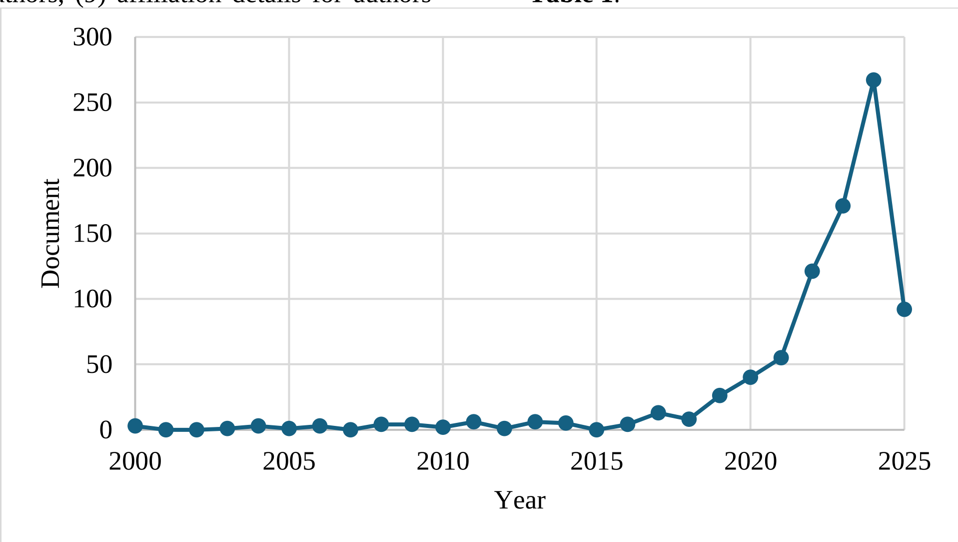

Fig. 2. Annual Distribution of Bibliometric and AI-Based Studies on Steel Slag Powder for Concrete Strength Enhancement.

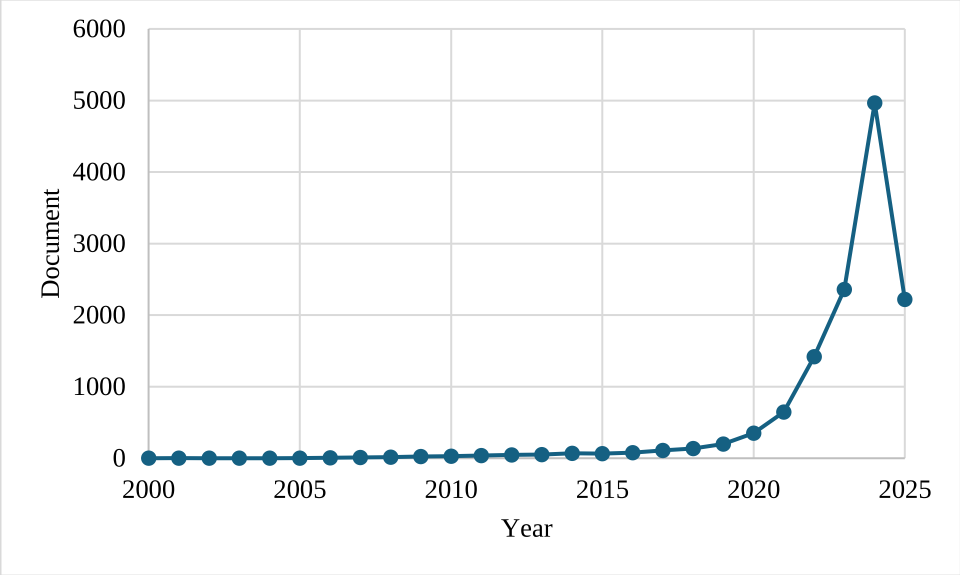

Fig. 3. Yearly Average Citations per Article in Studies on Steel Slag Powder and Concrete Strength.

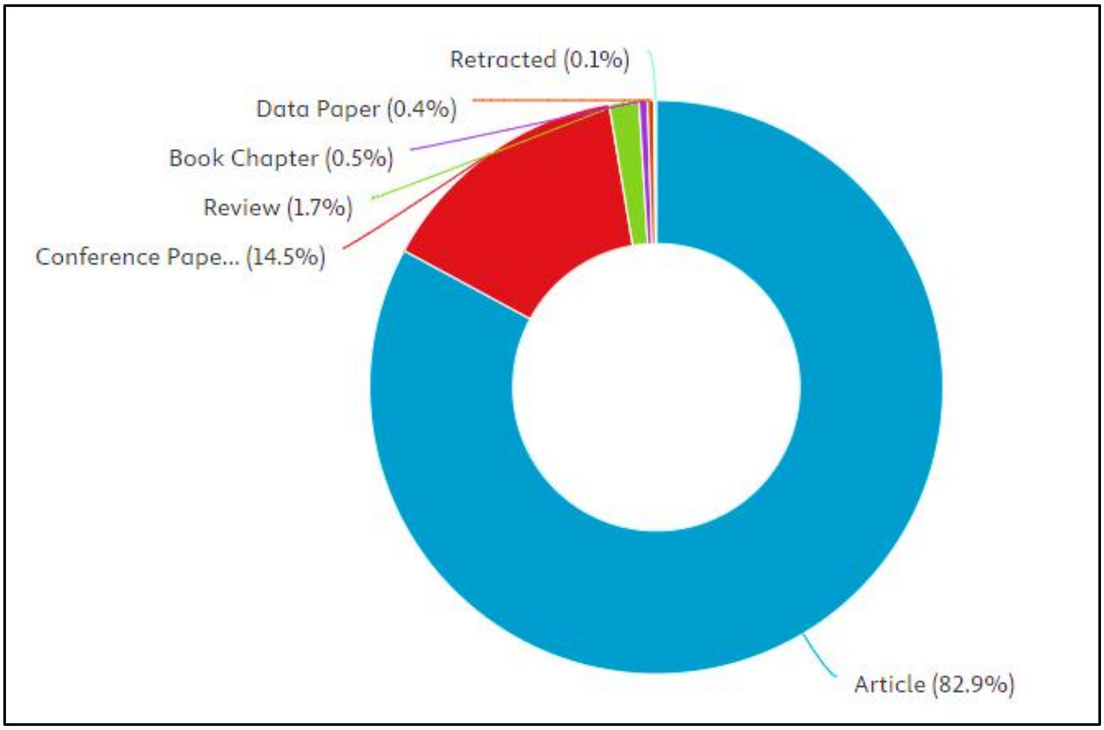

Fig. 4. Distribution of Documents by Type in Research on Steel Slag Powder for Concrete Strength.

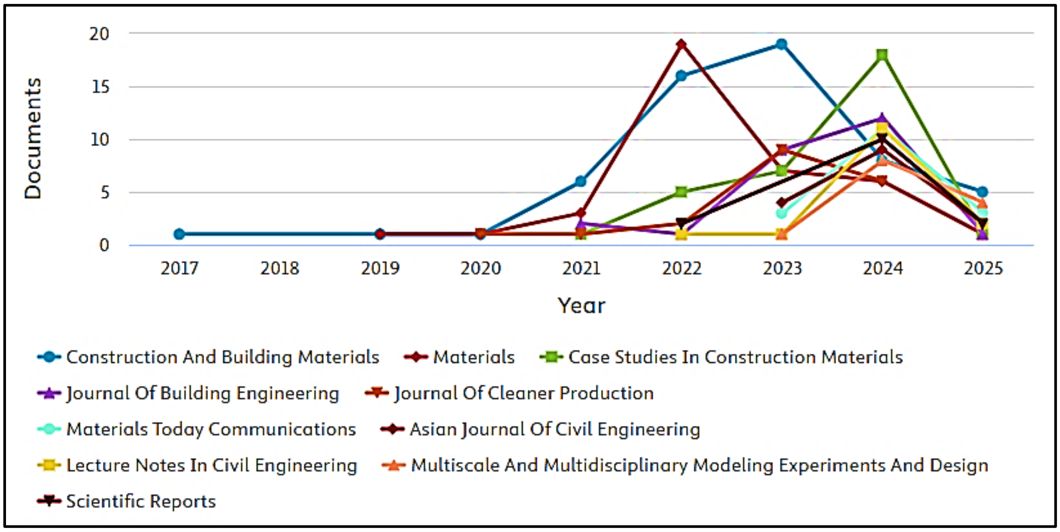

Fig. 5. Document per year by sources. in Research on Steel Slag Powder for Concrete Strength.

Table 1. The top 10 highly productive journals in Research on Steel Slag Powder for Concrete Strength.

Journal	TP	TC	Cite Score (2023)	Most cited publication	Times Cited	Publisher
Construction and Building Materials	15,336	211,152	13.8	Jaf, Dilshad Kakasor Ismael, et al. (2023)	242	Elsevier
Materials	30,074	173,808	5.8	Wang, X., et al. (2023)	172	Multidisciplinary Digital Publishing Institute (MDPI)
Case Studies in Construction Materials	2,295	17,401	7.6	Abdellatief, Mohamed, et al. (2023).	128	Elsevier
Journal of Building Engineering	7,051	70,200	10.0	Moein, Mohammad Mohtasham, et al (2023).	241	Elsevier
Journal of Cleaner Production	19,382	394,597	20.4	Mujtaba, Muhammad, et al. (2023)	442	Elsevier
Materials Today Communications	6,790	35,392	5.2	Nandhakumar, R., and K. Venkatesan (2023).	111	Elsevier
Asian Journal of Civil Engineering	560	1,516	2.7	Jibril, M. M., et al (2023).	9	Springer Nature
Lecture Notes in Civil Engineering	17,058	12,939	0.8	Amoura, Nasreddine, et al. (2022).	15	Springer Nature
Scientific Reports	88,503	661,612	7.5	Agu, Peter Chinedu, et al. (2022).	340	Springer Nature
Multiscale and Multidisciplinary Modeling, Experiments and Design	119	404	3.4	Kalita, Kanak, et al. (2022).	48	Springer Nature

TP= Total Publications, TC= Total Citation

Concerning scientific categories, 29.5% of total articles were categorized under Engineering, followed by materials science and Computer Science with 21.2% and 8.8% of the total articles, respectively as illustrated in **Fig. 6.** The total number of authors across all articles amounted to 159. Notably, “Amin, M.N.” authored a superior number of articles, with 18 articles. Following closely, “Khan, K.” contributed 15 articles, while “Javed, M.F.” authored 10 articles as shown in **Fig. 7**. In terms of the authors' H-index, " Javed, M.F." achieved the highest score of 51, followed by " Behnood, A.",and " Aslam, F." with an H-index of 46, as detailed in **Table 2.**

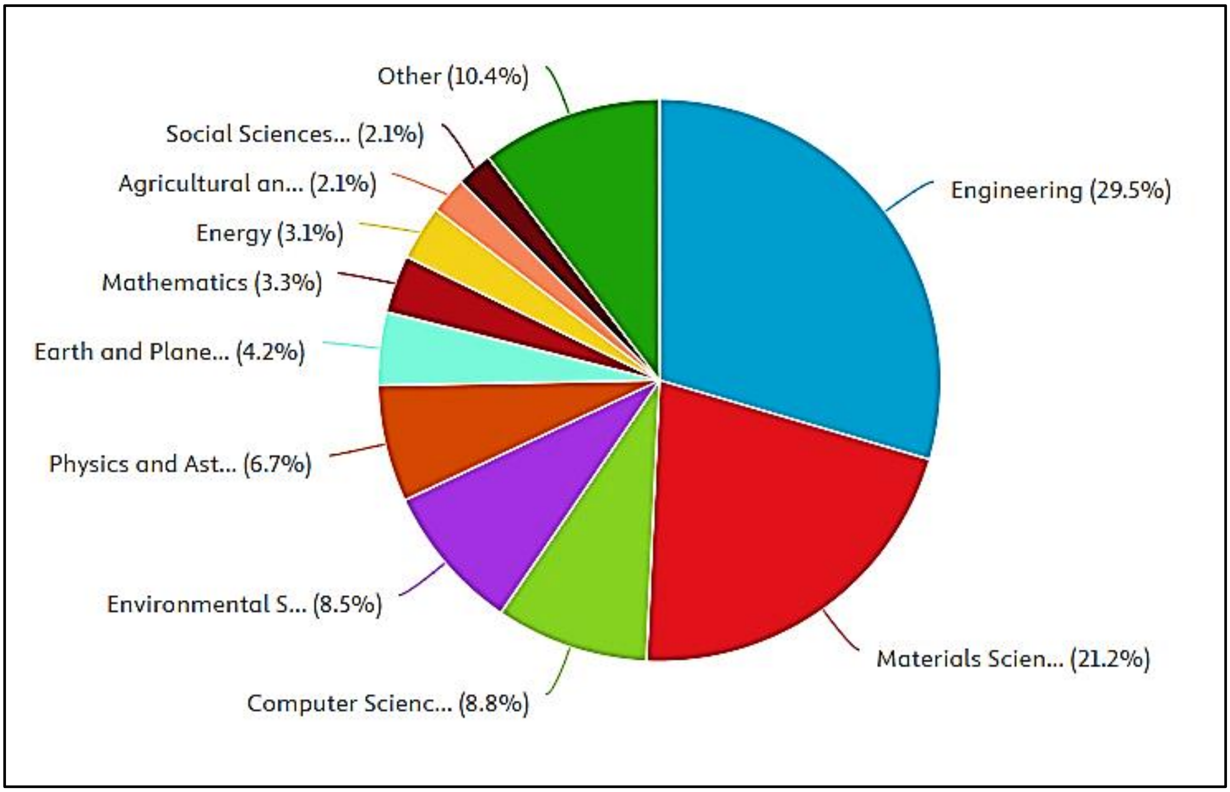

Fig. 6. Research field base publication on Steel Slag Powder for Concrete Strength.

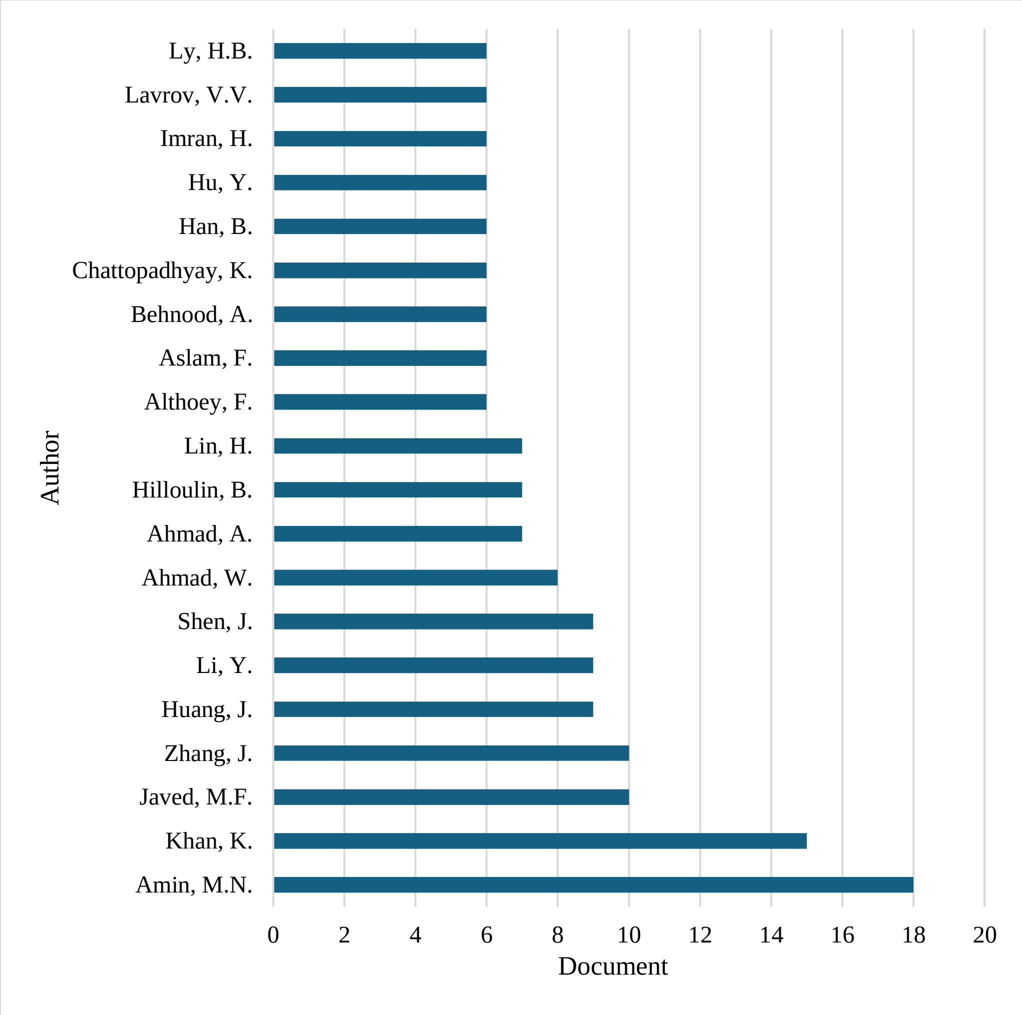

Fig. 7. Top 20 authors based on the number of articles on Steel Slag Powder for Concrete Strength.

Table 2. List of the 20 most prolific authors in Steel Slag Powder for Concrete Strength.

No	author	TP*	h-index	Current affiliation	Country
1.	Amin, M.N.	183	37	National University of Sciences and TechnologyThe institution will open in a new tab, Islamabad, Pakistan	Pakistan
2.	Khan, K.	160	34	King Faisal UniversityThe institution will open in a new tab, Al-Ahsa, Saudi Arabia	Saudi Arabia
3.	Javed, M.F.	207	51	COMSATS University Islamabad, Abbottabad CampusThe institution will open in a new tab, Abbottabad, Pakistan	Pakistan
4.	Zhang, J.	89	37	Hebei University of TechnologyThe institution will open in a new tab, Tianjin, China	China

5.	Huang, J.	113	28	Guangzhou UniversityThe institution will open in a new tab, Guangzhou, China	China
6.	Li, Y.	262	36	Beijing University of TechnologyThe institution will open in a new tab, Beijing, China	China
7.	Shen, J.	36	13	Beijing University of TechnologyThe institution will open in a new tab, Beijing, China	China
8.	Ahmad, W.	207	43	University of PeshawarThe institution will open in a new tab, Peshawar, Pakistan	Pakistan
9.	Ahmad, A.	172	43	King Faisal UniversityThe institution will open in a new tab, Al-Ahsa, Saudi Arabia	Saudi Arabia
10.	Hilloulin, B.	42	13	Institut de Recherche en Génie Civil et MécaniqueThe institution will open in a new tab, Nantes, France	France
11.	Lin, H.	67	16	Beijing University of TechnologyThe institution will open in a new tab, Beijing, China	China
12.	Althoey, F.	111	28	Najran UniversityThe institution will open in a new tab, Najran, Saudi Arabia	,Saudi Arabia
13.	Aslam, F.	125	46	Prince Sattam Bin Abdulaziz UniversityThe institution will open in a new tab, Al Kharj, Saudi Arabia	Saudi Arabia
14.	Behnood, A.	84	46	University of MississippiThe institution will open in a new tab, University, United States	United States
15.	Chattopadhyay, K.	136	21	University of TorontoThe institution will open in a new tab, Toronto, Canada	Canada
16.	Han, B.	36	14	University of Science and Technology BeijingThe institution will open in a new tab, Beijing, China	China
17.	Hu, Y.	32	11	University of Science and Technology BeijingThe institution will open in a new tab, Beijing, China	China
18.	Imran, H.	23	9	Al-Karkh University of ScienceThe institution will open in a new tab, Baghdad, Iraq	Iraq
19.	Lavrov, V.V.	74	10	Ural Federal UniversityThe institution will open in a new tab, Yekaterinburg, Russian Federation	Russian Federation
20.	Ly, H.B.	135	38	Đại học Công nghệ Giao thông vận tảiThe institution will open in a new tab, Hanoi, Viet Nam	Viet Nam

*TP= Total Publications.

The total number of keywords used in the articles was 1723. " Machine Learning" emerged as the most frequently utilized keyword, appearing 546 times, as depicted in **Fig. 8**. This was followed by " Slags" observed 341 times, and " Compressive Strength" documented 337 times. As shown in **Table 3**.

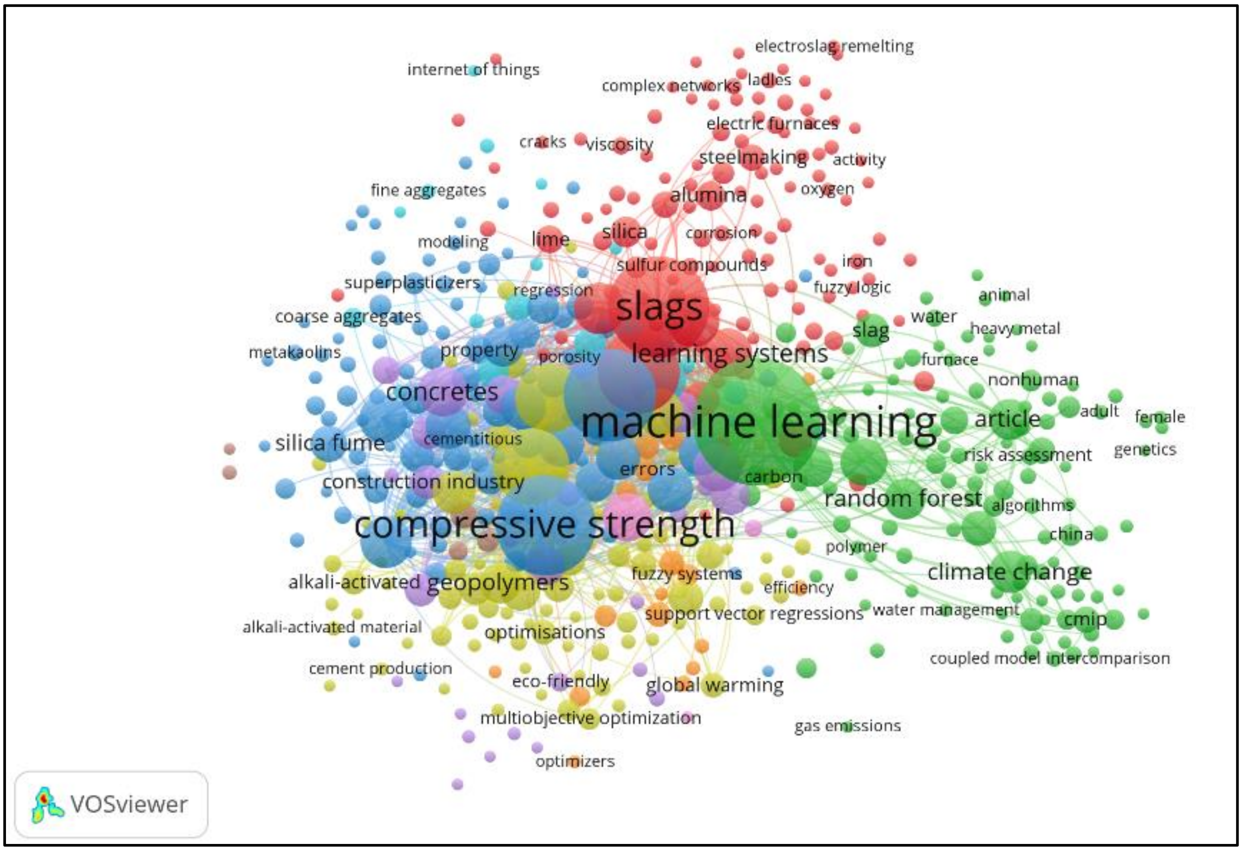

Fig. 8. Research Publications Categorized by Keywords in Steel Slag Powder for Concrete Strength.

China exhibited the top contributing country, publishing a total of 264 publications, as illustrated in **Fig. 9.** Additionally, it demonstrated robust collaborative connections with other countries, as shown in **Fig. 10.** In second place, India contributed 131 publications, followed by United States ranked third with 108 publications, as detailed in **Table 4.**

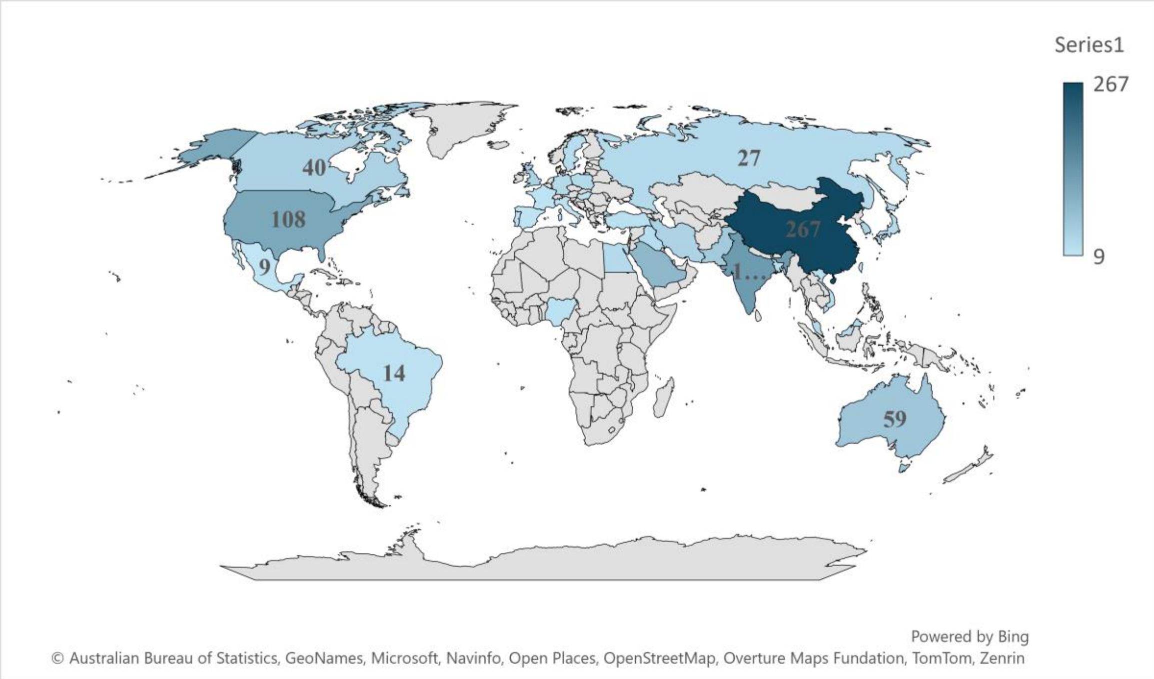

Fig. 9. Leading Countries in Research on Steel Slag Powder for Concrete Strength.

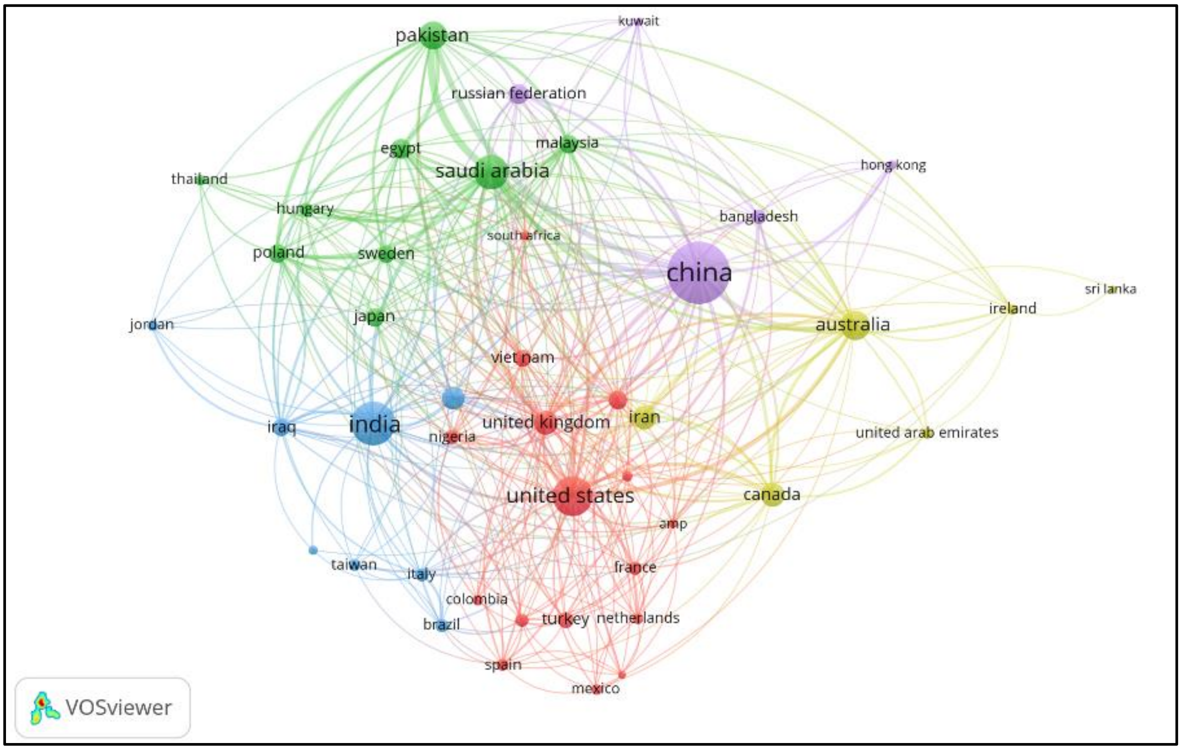

Fig. 10. Map of International Co-authorship in Steel Slag Powder for Concrete Strength Research.

Table 4. Most Productive Countries in Steel Slag Powder for Concrete Strength Research.

COUNTRY	No of articles
China	267
India	131
United States	108
Saudi Arabia	82
Australia	59
Pakistan	52
Canada	40
United Kingdom	39
Iran	38
South Korea	36
Egypt	27
Russian Federation	27
Germany	26
Malaysia	26
Poland	26
Japan	23
Iraq	22
Sweden	22
Viet Nam	21
Turkey	18
Nigeria	16
Bangladesh	15
Brazil	14
Italy	14
France	13
Hungary	13
Portugal	13
Taiwan	11
Spain	10
Mexico	9

The most productive affiliation was "Ministry of Education of the People's Republic of China" with 31 articles, followed by "COMSATS University Islamabad, Abbottabad Campus" with 51 articles and "King Faisal University" with 22 articles as shown in **Fig. 11**.

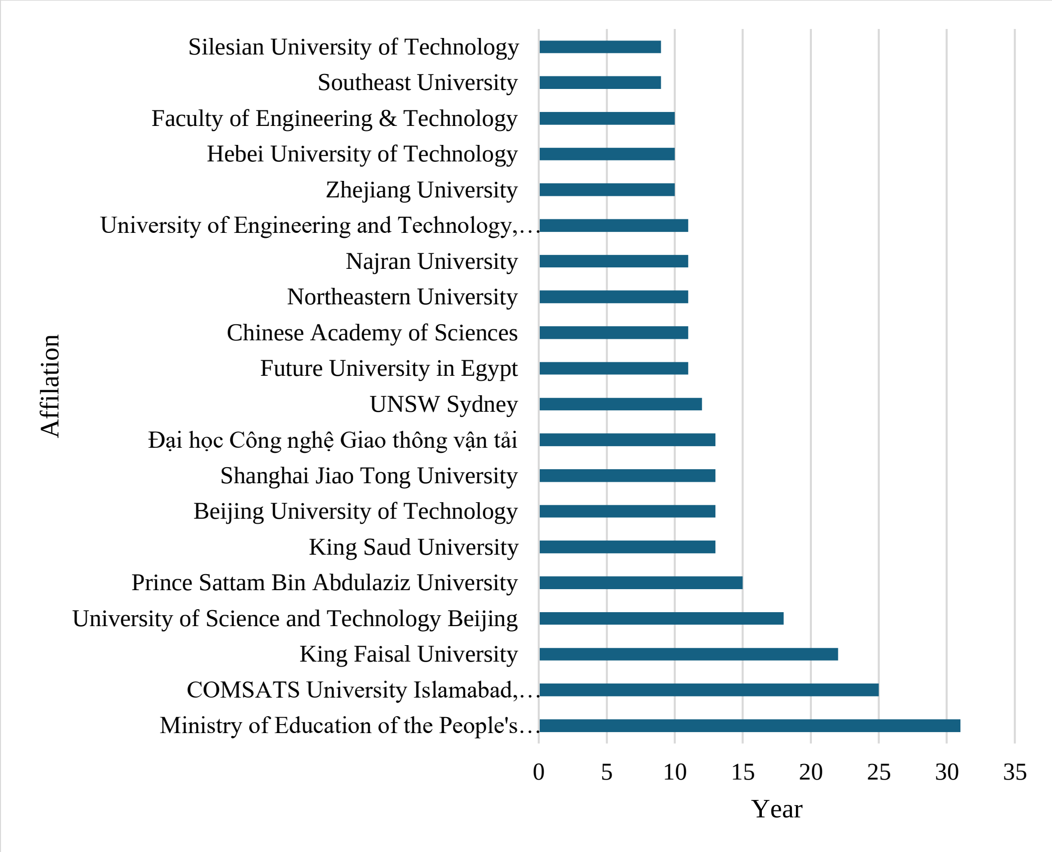

Fig. 11. Top 25 affiliations based on the number of documents in Steel Slag Powder for Concrete Strength Research.

4. Discussion

Steel Slag Powder (SSP) has gained significant attention in recent years as a promising supplementary cementitious material (SCM) for enhancing the strength and sustainability of concrete[28]–[30]. As a by-product of the steel-making process, steel slag contains valuable minerals such as calcium, silicon, and iron oxides, which exhibit latent hydraulic activity[28]–[33]. When finely ground and integrated into concrete mixtures, SSP enhances the compressive strength, durability, and environmental performance of concrete, contributing to the global push for more sustainable construction materials. The incorporation of SSP in concrete can reduce the reliance on traditional Portland cement, leading to lower CO_2 emissions and an eco-friendlier construction industry[34]–[36] .

The mechanical performance of SSP-modified concrete, particularly its compressive strength, is influenced by several factors, including the slag content, particle size, curing conditions, and the chemical composition of the slag[37]–[39]. The interaction between SSP and the cementitious material in the mix plays a crucial role in strength development, as the slag particles react with calcium hydroxide (CH) produced during hydration to form additional binding compounds like calcium silicate hydrate (C-S-H). The fineness of SSP, as well as the amount of cement replacement, significantly affects the early and late strength gain, with finer particles promoting a more effective chemical reaction with cement. However, the variability in the chemical composition of steel slag across different sources presents challenges in standardizing its use in concrete mixes, making it difficult to predict and optimize concrete performance .[40]–[42].

As the adoption of SSP-based concrete increases, it is essential to understand the mechanical properties and durability characteristics of these materials to ensure their effective application in construction. In this context, the role of artificial intelligence (AI) and machine learning (ML) in predicting concrete behavior has become a key area of interest[14], [18]. These technologies enable researchers to analyze complex datasets, uncover hidden patterns, and predict the mechanical performance of SSP-modified concrete based on various input parameters. ML algorithms, such as artificial neural networks (ANNs), support vector machines (SVMs), and regression models, have been increasingly employed to optimize SSP mix designs, forecast strength development, and assess long-term durability under different environmental conditions. The ability to predict concrete performance accurately reduces the need for time-consuming and costly experimental testing, enabling more efficient and sustainable concrete mix designs .[43], [44]

This study employs bibliometric analysis to assess the global trends and evolution of research on the use of steel slag powder (SSP) in concrete. Using data from Scopus and various bibliometric tools, including VOSviewer, the study systematically reviews the literature from 2000 to April 2025, highlighting the influential authors, institutions, countries, and research themes. The analysis identifies key research areas, including SSP as a cement replacement, the durability of SSP-modified concrete, and the use of AI and ML techniques to predict the performance of concrete mixes. The findings reveal a growing interest in sustainable concrete solutions, with countries like China, India, and the United States leading the charge in investigating industrial by-products like SSP to reduce the environmental impact of construction.

The study also highlights several emerging trends and research gaps in SSP-modified concrete. While there has been substantial progress in understanding the impact of SSP on compressive strength, there is a need for more comprehensive research on other properties such as flexural strength, shrinkage, and fatigue resistance. Additionally, the application of hybrid systems combining SSP with other industrial by-products like fly ash, slag, and silica fume is gaining traction. These hybrid mixtures are expected to improve the overall performance and sustainability of concrete while reducing the material costs. Another notable trend is the integration of AI-based approaches to optimize mix designs and predict the long-term performance of concrete structures in various environmental conditions. Techniques such as data-driven modeling, predictive analytics, and real-time monitoring systems are revolutionizing the way researchers and practitioners assess the behavior of SSP-modified concrete.

Despite the promising advantages of SSP-based concrete, several challenges remain. The variability in SSP quality, lack of standardized testing methods, and limited understanding of the long-term behavior of SSP in concrete systems hinder the widespread adoption of this material. Additionally, while AI and ML techniques have proven valuable in optimizing mix designs, challenges such as data scarcity, model interpretability, and computational requirements remain. To fully unlock the potential of AI-driven predictive models, more high-quality experimental data is required to train and validate these models, and further interdisciplinary collaboration is necessary to develop standardized testing protocols and guidelines for SSP-modified concrete.

5. Conclusion

- This study conducted a comprehensive bibliometric and AI-based analysis of global research on the use of steel slag powder (SSP) in concrete, particularly in relation to compressive strength enhancement.
- A total of 836 publications (2000–2025) were analyzed using Scopus data and bibliometric tools such as VOSviewer, uncovering research trends, key contributors, and collaboration networks.
- The results showed that China, India, and the United States are leading contributors in this field, reflecting their investments in sustainable infrastructure and industrial by-product utilization.
- The most frequently occurring keywords were "machine learning", "slags", and "compressive strength", indicating growing interest in data-driven performance prediction of SSP-modified concrete.
- Top-performing journals, including Construction and Building Materials and Journal of Cleaner Production, have served as key platforms for disseminating SSP-related research.
- The integration of machine learning (ML) and artificial intelligence (AI)

techniques (e.g., ANN, SVM, RF, GBM) has significantly improved the ability to predict concrete performance, reduce experimental costs, and optimize mix design.

- Despite its advantages, the widespread adoption of SSP-based concrete is challenged by slag variability, data limitations, and lack of standardization, which require further investigation and harmonization.
- This study provides valuable insights for researchers, engineers, and policymakers, supporting innovation in sustainable construction materials and intelligent data-driven concrete design.

5.1. Study Contributions

This study conducts an in-depth bibliometric review of the role of steel slag powder (SSP) in enhancing concrete strength, categorizing the research landscape into six major thematic domains: mechanical performance and strength development, durability and environmental sustainability, SSP as a supplementary cementitious material, optimization of mix design, integration with industrial by-products, and the application of artificial intelligence (AI) and machine learning (ML) for performance prediction. These thematic clusters reveal the evolving research priorities, experimental methodologies, and technological innovations shaping the use of SSP in sustainable construction materials.

Since 2000, there has been a significant upward trend in research output on SSP-based concrete, with notable growth from 2018 onward, peaking in 2024. This reflects an increasing global interest in resource-efficient construction practices and circular economy principles. The analysis identifies key contributing countries such as China, India, Iran, Turkey, and the United States—regions actively investing in infrastructure development and sustainable engineering. Leading institutions including Wuhan University of Technology, Tongji University, and the Indian Institute of Technology have emerged as major centers of innovation. Influential authors such as Li Jian, Singh R.K., and Zhang Yong have produced highly cited works, significantly advancing the understanding of SSP's chemical properties, microstructural behavior, and strength enhancement mechanisms. Journals such as Construction and Building Materials, Journal of Cleaner Production, and Cement and Concrete Composites serve as pivotal platforms for publishing advances in SSP research.

A major trend identified in this study is the integration of AI and ML techniques to model and predict the mechanical properties of SSP-incorporated concrete. Algorithms such as artificial neural networks (ANN), random forest (RF), support vector machines (SVM), gradient boosting machines (GBM), and decision trees (DT) have been applied to predict compressive strength, workability, and durability metrics. Advanced models like adaptive neuro-fuzzy inference systems (ANFIS) and gene expression programming (GEP) offer high accuracy in managing complex, nonlinear interactions between SSP content, curing conditions, water-to-binder ratios, and mechanical performance outcomes. Despite the promising results, challenges persist particularly in terms of data availability, model generalizability, and interpretability which require further exploration and validation through hybrid approaches and larger datasets.

This bibliometric and AI-based review offers a comprehensive synthesis of current research trends on steel slag powder in concrete, identifying key contributors, highlighting methodological advances, and outlining areas for future investigation. The findings emphasize the dual potential of SSP in reducing environmental impacts and improving concrete performance, while also demonstrating the transformative role of AI in accelerating material innovation. By bridging sustainable material science with intelligent data-driven techniques, this study contributes valuable insights for researchers, engineers, and policymakers striving for resilient and eco-efficient construction solutions.

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