



Systematic Review

Rice Husk Ash in Sustainable Concrete: A Hybrid Bibliometric and Systematic Review of Performance, Durability, and Data-Driven Material Design

Ali Istanbulu ¹ , Abubakar S. Mahmoud ^{2,*}, Rami Hamad ² and Majed A. A. Aldahdooh ²

¹ Civil and Construction Engineering Department, College of Engineering, A'Sharqiyah University, P.O. Box 42, Ibra 400, Oman; ali.istanbullu@asu.edu.om

² Department of Facilities and Construction Project Management, International College of Engineering and Management Affiliated with the University of Lancashire, UK, P.O. Box 2511, Muscat 111, Oman

* Correspondence: abubakar@icem.edu.om

Abstract

Rice husk ash (RHA) has emerged as a promising supplementary cementitious material (SCM) for sustainable construction due to its high silica content and potential to reduce the environmental impact of concrete. However, the evolution of RHA research and its transition toward advanced, data-driven material systems remain insufficiently synthesised. This study presents an integrated bibliometric analysis (BA) and systematic literature review (SLR) in which Scopus-indexed publications from 2007 to 2021 establish the historical evolution and structural dynamics of the field, while studies published between 2022 and 2026 are systematically reviewed to capture emerging developments and ensure contemporary relevance. The bibliometric analysis reveals a steady increase in research activity and identifies a shift from experimental material optimisation toward sustainability and computational modelling. When interpreted alongside the systematic review findings, this trend reflects a structured Past–Present–Future evolution of RHA research, from feasibility studies to microstructural optimisation and, more recently, to predictive and data-driven material design. The systematic review confirms that optimally processed RHA, typically at 10–30% cement replacement, enhances compressive strength, durability, and resistance to aggressive environments through improved pozzolanic reactivity and microstructural densification. Recent studies (2022–2026) further demonstrate the integration of machine learning, life-cycle assessment, and digital modelling approaches for performance prediction, mix optimisation, and sustainability evaluation. By linking bibliometric trends with scientific insights, this study identifies key research gaps, including the lack of standardisation in RHA production, limited large-scale validation, and weak integration of experimental and computational approaches, and proposes an integrated five-tier framework, moving from material standardisation through performance validation and computational intelligence to sustainability integration and industrial-policy adoption, to guide future research and implementation. The findings highlight the transition of RHA from a conventional SCM to a component of intelligent, sustainable, and circular construction systems, providing a foundation for future research and industrial application.

Keywords: rice husk ash; supplementary cementitious materials; bibliometric analysis; machine learning; circular economy; concrete durability; microstructure



Academic Editors: Gregor Kravanja and Natalija Bede Odorčić

Received: 19 June 2026

Revised: 7 July 2026

Accepted: 10 July 2026

Published: 23 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The construction industry plays a critical role in global economic development; however, it is also one of the largest contributors to environmental degradation, particularly due to the high carbon emissions associated with cement production. It is widely reported that cement manufacturing accounts for approximately 7–8% of global CO₂ emissions, making it a key target for decarbonisation strategies in the built environment [1–3]. Consequently, increasing attention has been directed toward the development and utilisation of supplementary cementitious materials (SCMs) to reduce clinker content and improve the sustainability of concrete systems. Rice husk (RH), an abundant agricultural by-product generated during rice milling, presents significant environmental challenges due to its large volume and disposal practices. In major rice-producing regions, particularly in Asia and Africa, conventional disposal methods such as open burning and landfilling contribute to greenhouse gas emissions and environmental pollution [4,5]. The controlled combustion of RH to produce rice husk ash (RHA) has emerged as an effective waste-valorisation strategy, transforming agricultural residues into a high-silica pozzolanic material suitable for construction applications [5,6].

RHA is characterised by its high amorphous silica content and large specific surface area, which contribute to its strong pozzolanic reactivity and ability to enhance cement hydration. Recent studies have confirmed that partial replacement of cement with RHA improves compressive strength, reduces permeability, and enhances resistance to chloride ingress and sulphate attack due to the formation of additional calcium–silicate–hydrate (C–S–H) gel and improved microstructural densification [1,2,7]. Furthermore, RHA has been successfully incorporated into advanced cementitious systems, including high-performance concrete (HPC) and ultra-high-performance concrete (UHPC), where it enhances durability and long-term performance [8,9]. Beyond its mechanical benefits, RHA plays a significant role in sustainable construction by reducing the environmental footprint of concrete. Life-cycle assessment studies demonstrate that replacing cement with RHA can significantly lower CO₂ emissions and energy consumption, while simultaneously promoting resource efficiency and waste utilisation [1,2,10]. These advantages position RHA as a key material within circular-economy frameworks, where agricultural waste is converted into value-added construction products [4,11].

In recent years, the field has undergone a notable transformation driven by advancements in computational and digital technologies. Machine learning (ML) and data-driven modelling approaches have been increasingly applied to predict compressive strength, optimise mix design, and evaluate durability performance of RHA-based concrete systems [8,12–14]. These approaches enable the analysis of complex nonlinear relationships between material parameters and performance outcomes, significantly reducing experimental effort while improving predictive accuracy. Additionally, the integration of life-cycle assessment (LCA) with machine learning models has facilitated the simultaneous optimisation of environmental and mechanical performance, supporting the development of low-carbon construction materials [1,15].

Despite the extensive body of research on RHA, existing studies predominantly focus on isolated aspects such as material properties, processing techniques, or environmental performance, with limited integration across these domains. Many studies concentrate on mechanical and durability performance under controlled laboratory conditions without adequately addressing large-scale applicability or long-term field performance [2,7,16]. Similarly, research on RHA production and processing has largely been conducted independently of performance optimisation, resulting in variability in material properties and challenges in standardisation [5,17]. Furthermore, although recent studies have introduced machine learning and computational modelling approaches, these developments are of-

ten treated as standalone innovations rather than being systematically integrated with experimental and sustainability research [8,12–14]. In addition, the application of RHA in emerging construction technologies, such as geopolymer systems, alkali-activated binders, and digital construction processes, remains relatively limited and fragmented [18,19].

From a methodological perspective, previous review studies have typically employed either bibliometric analysis (BA) or systematic literature review (SLR) independently. While bibliometric studies provide insights into research trends, collaboration networks, and thematic development, they often lack detailed scientific interpretation [20,21]. Conversely, systematic reviews offer in-depth analysis of material behaviour and performance but may not capture the broader evolution and structural dynamics of the research field [3,4]. This separation limits the ability to develop a comprehensive understanding of how RHA research is evolving in response to sustainability challenges and digital transformation in construction materials.

To address these limitations, this study adopts an integrated bibliometric analysis (BA) and systematic literature review (SLR) to provide a comprehensive and analytical assessment of RHA research in concrete. The bibliometric analysis was limited to Scopus-indexed publications up to 2021 to ensure data completeness, citation maturity, and stability of the bibliometric indicators reported in Section 4, while recent publications (2022–2026) were incorporated through a dedicated systematic literature review (Section 5) to capture emerging developments in machine learning, life-cycle assessment, and digital material systems, and to maintain contemporary relevance. By linking quantitative research patterns from the BA with qualitative scientific insights from the SLR, and by explicitly connecting the two strands of evidence in an integrated discussion (Section 6), this study moves beyond a descriptive review of historical trends to provide a structured Past–Present–Future narrative of how RHA research has evolved, culminating in a proposed framework (Section 8) for guiding future research and industrial adoption of RHA as a component of sustainable, data-driven, and intelligent construction systems.

Table 1 positions this study against four representative prior reviews of RHA in concrete, spanning narrative reviews from before the field’s computational turn [22,23], a purely bibliometric treatment [24], and a recent narrow-scope systematic review [25]. No prior review combines a real, Scopus-verified bibliometric analysis with a comparably sized systematic corpus, a dedicated machine learning and data-driven modelling treatment, quantified sustainability comparison, an explicit standardisation and industrial-adoption analysis, and an integrated adoption framework; this combination, rather than any single element in isolation, is the principal methodological contribution of this study.

Table 1. Positioning of this study against representative prior reviews of RHA in concrete.

Review	BA	Real-Database SLR	ML/ Data-Driven	Sustainability (Quantified)	Standardisation/ Industrial	Integrated Framework
Thomas (2018) [22]	No	No	No	Qualitative only	No	No
Siddika et al. (2021) [23]	No	No	No (pre-dates ML wave)	Qualitative only	Brief mention	No
Amin et al. (2022) [24]	Yes	No	No	No	No	No
Samarajeewa et al. (2026) [25]	No	Yes (narrow; n = 19, nanomaterial- specific)	Partial (nano-RHA only)	No	No	No
This study (2026)	Yes (606 docs, 2007–2021)	Yes (1423-record corpus; 39 curated)	Yes (dedicated section; corpus-wide trend, Figure 1)	Yes (Tables 2 and 3)	Yes (Section 5.8; ASTM C618 [26], EN 197-1 [27])	Yes (five-tier, Section 8)

The remainder of this paper is organised as follows. Section 2 outlines the theoretical foundations of the study. Section 3 details the hybrid BA-SLR methodology, including the search and eligibility criteria applied to both strands. Section 4 presents the bibliometric results for the 2007–2021 period. Section 5 reports the systematic review of recent developments published between 2022 and 2026, organised thematically. Section 6 integrates the two strands of evidence into a single Past–Present–Future discussion. Section 7 synthesises the identified research gaps, Section 8 proposes an integrated framework for future research and industrial adoption, and Section 9 concludes the study.

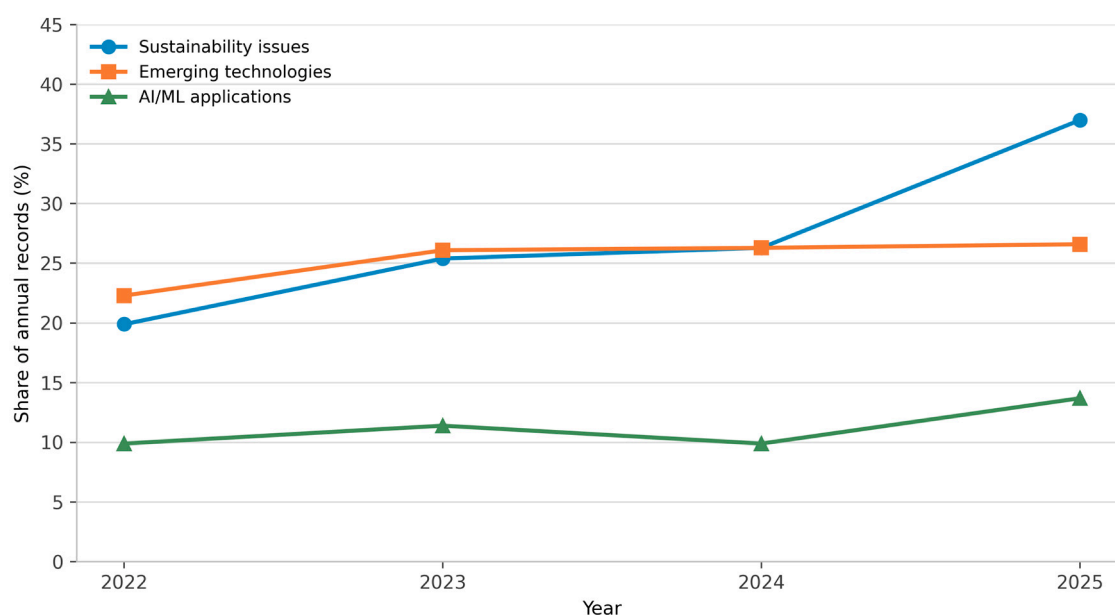


Figure 1. Thematic prevalence trends in the 2022–2026 RHA-concrete corpus, by year (Scopus, $n = 1423$; partial-year 2026 excluded).

Table 2. Summary of foundational studies shaping RHAC research (2007–2021).

Reference	Study Objective	Summary of Findings
Saraswathy and Song [28]	Corrosion performance of RHA-blended concrete	RHA enhances concrete strength by forming C–S–H-based gel.
Chindaprasirt et al. [29]	Sulphate resistance of blended cement containing FA and RHA	RHA and FA both improve sulphate resistance; RHA is more effective.
Ganesan et al. [30]	Optimal level of cement replacement with RHA for strength and permeability	Up to 30% RHA can replace cement without compromising strength or permeability.
Chindaprasirt and Rukzon [31]	Strength, porosity and corrosion resistance of ternary Portland cement–RHA–FA mortar	Ternary blends enhance strength and corrosion resistance.
Habeeb and Fayyadh [32]	Impact of RHA particle size on mechanical properties and drying shrinkage	Finer RHA particles reduce shrinkage and improve mechanical properties.
Givi et al. [33]	Impact of RHA on strength, permeability and workability of binary blended concrete	Ultrafine RHA particles improve workability and strength.

Table 2. Cont.

Reference	Study Objective	Summary of Findings
Van Tuan et al. [34]	Impact of RHA on hydration and microstructure of UHPC	RHA improves hydration and compressive strength of UHPC.
Zain et al. [35]	Use of RHA as a supplementary cementitious material	Controlled burning and grinding are essential for high-quality RHA.
Khan et al. [16]	Potential of RHA for environmental waste reduction	RHA improves concrete properties while providing environmental benefits.
Karim et al. [36]	Fabrication of a non-cement binder (NCB) using RHA and sodium hydroxide	Optimal strength achieved when NCB is combined with 30% RHA.
Chopra et al. [37]	Strength, permeability and microstructure of self-compacting concrete (SCC) with RHA	RHA enhances the strength and durability of SCC.
Bie et al. [38]	Impact of burning conditions and RHA blend ratio on cement behaviour	Optimal 10% RHA replacement significantly improves cement strength.
Zareei et al. [39]	RHA as a partial cement replacement in high-strength concrete	15% RHA replacement enhances compressive strength by ~20%.
Kang et al. [9]	RHA as a reactive filler in UHPC	RHA improves UHPC strength through enhanced pozzolanic reactions.

Table 3. Quantitative synthesis of RHA replacement level and reported compressive-strength and durability outcomes across screened studies.

RHA Replacement Level	Reported Compressive-Strength Effect	Reported Durability Effect	Source(s)
5–10%	Up to +29% vs. control in pervious concrete; optimum replacement level in several individual studies	Reduced porosity and chloride penetration consistent with the broader 0–30% trend [40]	Khankhaje et al. [40]
10–15%	UHPC: +9.78% compressive, +25.09% tensile, +10.9% flexural vs. control	Not separately reported at this band in [41]	Mohamed et al. [41]
10–25%	+20–31.7% at 28 days across reviewed soil–cement and SCM studies	Reduced porosity and chloride penetration reported across the same replacement range [42]	Yin et al. [42]
15%	~20% compressive-strength gain reported (Table 2)	~25% reduction in chloride penetration reported (Table 2)	Zareei et al. [39]
20–30% (cement)	+25% at 20% [43]; strength gains taper toward 30% in the wider database [44]	Chloride penetration falls below 1000 coulombs (low permeability) once replacement exceeds 30% across a 1000+ data-point database; mass loss after sulphuric-acid exposure, water absorption, and porosity all decrease monotonically to 30%, while electrical resistivity and chloride-diffusion resistance improve over the same range; 30% (cement) identified as the database-wide optimum	Al-Alwan et al. [43]; Oztürk et al. [44]

Table 3. Cont.

RHA Replacement Level	Reported Compressive-Strength Effect	Reported Durability Effect	Source(s)
20% (sand)	Not separately reported at this band	Database-wide optimum for RHA as a sand replacement is lower than for cement replacement (~20%); ultrasonic pulse velocity indicates doubtful concrete quality beyond this level when RHA replaces sand	Oztürk et al. [44]
25–30%	Generally declining strength relative to the 5–15% range, though frequently still $\geq$ OPC control; upper edge of the safe range identified in foundational studies (Table 2)	Durability indicators continue improving to 30% even where strength gains plateau or decline, indicating that strength and durability optima do not necessarily coincide	Yin et al. [42]; Ganesan et al. [30]; Oztürk et al. [44]

2. Theoretical Background

This study is grounded in the theoretical perspectives of sustainable development and circular economy, which emphasise the efficient use of resources, waste valorisation, and reduction in environmental impact in construction systems [4,10]. The conversion of rice husk (RH) into rice husk ash (RHA) is a practical application of these principles, transforming agricultural waste into a high-value supplementary cementitious material (SCM) that supports low-carbon construction. In addition to sustainability theory, this study draws on innovation diffusion theory (IDT) to explain the adoption and integration of RHA in construction practices. According to IDT, the uptake of new materials depends on factors such as relative advantage, compatibility with existing systems, and ease of implementation. In the context of RHA, challenges such as variability in material properties, lack of standardisation, and limited field validation hinder its widespread adoption [16,17]. These barriers highlight the importance of aligning technological development with industry requirements to facilitate large-scale implementation.

Furthermore, the study incorporates a data-driven innovation perspective, reflecting the increasing role of computational tools such as machine learning (ML) and predictive modelling in construction materials research. Recent studies demonstrate that ML-based approaches can optimise mix design, predict material performance, and support decision-making in sustainable construction systems [8,12,14]. This shift toward data-driven methodologies represents a transition from traditional experimental approaches to intelligent material-design frameworks. By integrating sustainability theory, innovation diffusion theory, and a data-driven innovation perspective, this study provides a conceptual foundation for analysing the evolution of RHA research. These frameworks support the interpretation of the bibliometric and systematic review findings reported in Sections 4–6 and underpin the adoption-oriented framework proposed in Section 8.

3. Methodology

3.1. Bibliometric Analysis (2007–2021)

This study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to identify, select, and analyse publications on the utilisation of RHA as a cementitious/pozzolanic material in concrete construction. Figure 2 presents the PRISMA flow diagram for the bibliometric dataset. The Elsevier Scopus database was used to identify and extract publications from 2007 to 2021—a cut-off selected to ensure data completeness, citation maturity, and stability of the bibliometric indicators reported in

Section 4 (Section 3.2 describes how the more recent literature was incorporated). A total of 1459 documents containing the relevant keywords were retrieved using the TITLE-ABS-KEY search criteria. Duplicate and unrelated records were removed through an additional TITLE-based screening, yielding 606 documents for analysis. Duplicate and off-topic record removal and application of the inclusion and exclusion criteria were carried out by a single reviewer (the lead author, who conducted the literature search and data curation); the resulting dataset and screening decisions were subsequently checked by the co-authors. No automated screening software was used at this stage; deduplication and eligibility screening were performed manually within Scopus and a reference spreadsheet. Bibliometric analysis (BA) was used to examine the research landscape through co-authorship, co-occurrence, and citation analyses performed in VOSviewer version 1.6.16 [45]. No citation threshold was applied at the data-assembly stage, to avoid bias toward highly cited and older publications and to ensure that both foundational and more recent studies within the dataset are adequately represented. This should be distinguished from the minimum-document and minimum-citation settings reported later in Sections 4.2 and 4.4 (a 2-document/2-citation setting for the co-authorship map and a 5-document/5-citation setting for the source-citation map): those are VOSviewer visualisation parameters, applied solely to keep the network maps legible, and they do not remove any record from the underlying bibliometric dataset used for the counts and trends reported in Section 4. To enhance transparency and reproducibility, explicit inclusion and exclusion criteria were applied during screening: only English-language, peer-reviewed journal articles, conference papers, and review articles indexed in Scopus were retained, while editorials and other non-peer-reviewed materials were excluded from the eligibility assessment. For transparency, Table 4 reports the document-type composition of the full 606-record dataset exactly as retrieved from Scopus; the six errata, two retracted articles, and one note it lists (nine records, 1.5% of the dataset) are shown for completeness but, being non-substantive or withdrawn items, were not treated as primary research contributions and do not materially affect the co-authorship, co-occurrence, and citation structures interpreted in Section 4. Studies were retained only where they explicitly addressed RHA as a supplementary cementitious material, pozzolan, or binder in construction-related applications; publications concerned solely with the energy generation or agricultural use of rice husk were excluded.

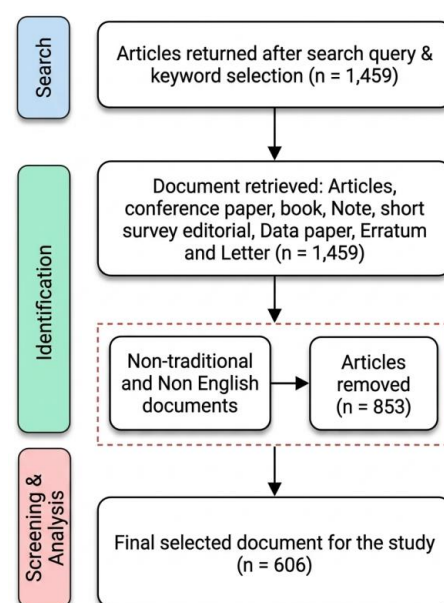


Figure 2. PRISMA flow diagram for the bibliometric dataset (2007–2021).

Table 4. Publication types for RHAC publications in Scopus (2007–2021).

Document Type (DT)	Total Publications (TP)	% of Total Publications
Article	426	70.30
Conference Paper	150	24.75
Review	14	2.31
Book Chapter	7	1.16
Erratum	6	0.99
Retracted	2	0.33
Note	1	0.17

3.2. Systematic Literature Review of Recent Developments (2022–2026)

To complement the bibliometric baseline and capture developments published after the 2021 data-extraction date, a second Scopus search was conducted for the period 2022–2026, using the same database and an equivalent TITLE-ABS-KEY search strategy as the 2007–2021 analysis: (“rice husk ash” OR “RHA”) AND (“concrete” OR “cement” OR “mortar” OR “supplementary cementitious material*”), restricted to Article, Review, and Conference Paper document types in English. This search, conducted on 22 June 2026, identified 1444 records. After removing 13 duplicate records ($n = 1431$) and excluding a further 8 records found at title/abstract screening not to concern RHA in a construction or cementitious context (e.g., biomedical, catalytic, or unrelated agricultural applications that matched the search string incidentally), a final corpus of 1423 records remained for the 2022–2026 period. Removal of the 13 duplicate records and exclusion of the 8 records unrelated to RHA in a cementitious context were carried out at title/abstract level by a single reviewer, with the retained corpus subsequently checked by the co-authors. This is more than thirty times the number of studies considered in earlier drafts of this section, which relied on a non-systematic web search; that approach is no longer used, and the analysis reported in Sections 4.5 and 5 is based entirely on this Scopus-derived corpus.

The same eligibility criteria applied to the bibliometric dataset were retained for this corpus: only English-language, peer-reviewed journal articles, conference papers, and review articles that explicitly addressed RHA as a supplementary cementitious material, pozzolan, or binder were eligible, while editorials, non-peer-reviewed notes, and studies concerned solely with the energy or agricultural use of rice husk were excluded. Given the size of the resulting corpus ($n = 1423$), two complementary analytical strategies were used. First, the full corpus was classified at scale using an automated, reproducible term-frequency method: titles and abstracts were screened computationally against keyword sets defined for each of the six thematic categories used to organise the bibliometric clusters in Section 4 (the full keyword lists and classification script are available from the corresponding author on request; the classification method is described in Section Search Limitations), allowing every record to be assigned to zero, one, or more themes. This corpus-level analysis is reported in Section 4.5 and Table 5. Second, a smaller set of methodologically notable studies ($n = 39$) was selected for detailed narrative discussion in Section 5 (Table 6), chosen to illustrate each of the six themes with concrete examples and to highlight studies of particular methodological interest (e.g., novel ML architectures, large comparative benchmarks, or notable life-cycle assessments). This subset is explicitly a curated, illustrative sample rather than an exhaustive or randomly drawn one, and should not be read as statistically representative of the full 1423-record corpus; the corpus-level analysis in Table 5 serves that representative role instead. Data collection proceeded as follows. At the corpus level ($n = 1423$), theme assignments and study counts were extracted automatically from titles

and abstracts using the keyword-based term-frequency script described in Section Search Limitations (keyword sets available from the corresponding author on request); because this step is fully scripted and deterministic, it does not depend on individual reviewer judgement, and its outputs were validated by manually inspecting category samples for false positives. For the curated subset ($n = 39$) discussed in Section 5, the lead author read each study in full and extracted the replacement levels, performance and durability outcomes, and methodological details summarised in Tables 3 and 6; these extractions were subsequently reviewed by the co-authors. Bibliometric variables (document type, authorship, country, funder, and citation counts) were exported directly from Scopus and VOSviewer without manual re-entry.

Table 5. Mapping of recent (2022–2026) literature themes to key findings and study counts.

Theme	n (% of Corpus, N = 1423)	Key Findings Across Reviewed Literature
AI/ML applications	171 (12.0%)	Machine learning and deep learning form a stable, internationally distributed share of annual output (9.9–13.7% per year, 2022–2025; Figure 1), with hybrid, symbolic regression, and ensemble/metaheuristic-optimised models reported across the corpus achieving high predictive accuracy and, in some cases, interpretability [8,14,46–50], jointly optimising mechanical and environmental performance [15].
Emerging technologies	372 (26.1%)	The second-largest theme (26.1%, growing steadily from 22.3% in 2022 to 26.6% in 2025). Geopolymer, alkali-activated, and novel composite systems incorporating RHA show promising high-temperature, microstructural, and durability performance [18,19,51–53], and ultrafine or ternary processing further improves strength and durability [7,54]; RHA-specific digital twin applications remain unreported in the screened literature.
New methodologies	122 (8.6%)	Production/processing methods are a stable, comparatively modest share of the corpus (8.6%, essentially flat 2022–2025). Fluidised-bed combustion and microwave-assisted pyrolysis improve the consistency and scalability of RHA production [5]; computational material-design approaches are beginning to be proposed for binder optimisation [55], and pilot-scale silica-extraction routes are emerging (semi-pilot-scale study, 2023).
Sustainability issues	418 (29.4%)	The largest and fastest-growing theme in the corpus, rising from 19.9% of annual records in 2022 to 37.0% in 2025 (Figure 1). Database and life-cycle studies confirm reductions in CO ₂ emissions and production cost without compromising performance [2,56], and position RHA within circular-economy frameworks for agricultural-waste valorisation [1].
Industry adoption	12 (0.8%)	Remains the most marginal advanced theme alongside policy (0.8% of the corpus, year-on-year stable at 0.3–1.1%). Ternary-blend studies [11] demonstrate technical viability for industrial-scale eco-friendly concretes, but reported applications remain predominantly laboratory-scale, with no large-scale field validation identified.
Policy developments	4 (0.3%)	Essentially absent at corpus scale (4 of 1423 records, all incidental mentions rather than substantive policy analysis), confirming with quantitative evidence the qualitative finding that no major new policy instruments specific to RHA emerged in 2022–2026; valorisation continues to be shaped by frameworks established before 2022, such as Malaysia’s Bio-Circular-Green Economy Model and India’s Waste-to-Wealth Mission (Section 4.3).

Table 6. Summary of recent (2022–2026) studies reviewed in the systematic literature review (n = 39).

Study	Theme	Key Finding
Ozturk et al. [2]	Sustainability issues	Database-driven evaluation shows RHA concrete reduces CO ₂ emissions and production cost while maintaining eco-strength efficiency.
Bameri et al. [11]	Industry adoption	Eco-friendly ternary concrete (silica fume, waste glass powder, GGBFS) shows enhanced strength and sulphate resistance.
Bayaidah et al. [7]	Emerging technologies	Ultrafine RHA binary mixes improve strength, durability, and microstructure while reducing carbon emissions.
Aliyu [5]	New methodologies	Fluidised-bed combustion and microwave-assisted pyrolysis improve RHA uniformity and reduce residual carbon content.
Kashem et al. [8]	AI/ML applications	Hybrid machine learning algorithms achieve high predictive accuracy for compressive strength of RHA concrete.
Datta [15]	AI/ML applications	ML-based multi-objective optimisation simultaneously improves mechanical performance and reduces environmental impact.
Behfarnia et al. [18]	Emerging technologies	Natural pozzolan-based geopolymers incorporating RHA show high-temperature resistance.
Rashidi et al. [19]	Emerging technologies	Multiscale assessment shows favourable microstructure for RHA-relevant alkali-activated binder systems.
Alamiery [14]	AI/ML applications	Symbolic regression models predict compressive strength with interpretable variable relationships.
Tien [55]	New methodologies	Computational material-design approaches proposed for low-carbon binder systems.
Pham and Tran [1]	Sustainability issues	Circular-economy framing of agricultural waste ash within low-carbon binder systems.
Paul et al. [57]	AI/ML applications	ML and DL models predict RHA concrete compressive strength with high reliability across training and testing phases.
Hoang and Nguyen [58]	AI/ML applications	diffGrad-optimised deep learning improves compressive-strength estimation accuracy for RHA-blended high-strength concrete.
Karim et al. [59]	AI/ML applications	SHAP and PDP analyses identify the mix variables driving ML-predicted compressive strength of RHA concrete.
Amin et al. [60]	AI/ML applications	Optimised and hyper-tuned ML models improve prediction of RHA concrete performance as an SCM.
Al-Shamasneh et al. [13]	AI/ML applications	Twelve ML algorithms compared for compressive-strength forecasting; SVR, GPR and NuSVR models perform best.
Li et al. [47]	AI/ML applications	Hybrid ANN model optimised via a reptile search algorithm improves compressive-strength prediction for RHA concrete.
Al-Hashem et al. [46]	AI/ML applications	ANN and GEP models accurately predict the compressive strength of concrete containing fly ash and RHA.

Table 6. Cont.

Study	Theme	Key Finding
Alyami et al. [12]	AI/ML applications	Interpretable ML-based models estimate the compressive strength of RHA concrete with high accuracy.
Fernando et al. [51]	Emerging technologies	Long-term durability assessment of blended fly ash–RHA alkali-activated concrete confirms sustained performance.
Hamada et al. [61]	Emerging technologies	The literature review identifies RHA’s current role and future directions in geopolymer concrete research.
Hasan et al. [62]	New methodologies	RHA integration as an SCM enables the production of sustainable high-strength concrete.
Jing et al. [63]	Sustainability issues	Multi-walled carbon nanotubes combined with RHA improve durability and confirm the resulting concrete’s environmental friendliness.
Cárdenas-Pulido et al. [52]	Emerging technologies	RHA-derived alternative sodium silicate enables ambient-cured geopolymer concrete with structural-grade properties.
Ullah et al. [54]	Emerging technologies	Ternary RHA–extracted-microsilica blends improve mechanical and durability performance of high-strength concrete.
Wang et al. [64]	Emerging technologies	RHA–rubber-fibre concrete shows distinct erosion-degradation behaviour under hygrothermal exposure.
Daniyal et al. [65]	Emerging technologies	Increasing the RHA-to-fly ash ratio improves the compressive strength of geopolymer concrete.
Miah et al. [56]	Sustainability issues	Experimental and data-based modelling confirm RHA reduces environmental impact while maintaining workability and strength.
[66]	Sustainability issues	RHA is confirmed as an eco-friendly cement substitute, improving strength and durability while reducing carbon emissions.
[67]	Sustainability issues	Life-cycle assessment of RHA-containing bio-concrete wall systems shows favourable carbon footprint outcomes compared with conventional masonry.
[68]	Emerging technologies	RHA shown to be a viable partial cement replacement in 3D-printable concrete mixes.
[69]	New methodologies	Semi-pilot-scale sol–gel process achieves high-yield, high-purity silica extraction from RHA.
[70]	Future directions	Comprehensive review synthesises RHA production, properties and applications, identifying directions for further research.
Li et al. [71]	AI/ML applications	Combines experimental testing with a dynamic compressive-strength ML model linking RHA calcination temperature and particle size to performance.
Yang et al. [48]	AI/ML applications	XGBoost hybridised with metaheuristic optimisers (NGO, APO, CFOA) improves compressive-strength prediction; cement content is the most influential variable.
Çaglar [49]	AI/ML applications	Ensemble learning and multi-objective optimisation (APO, EEFO, TOPSIS) balance compressive strength against CO ₂ /SO ₂ emissions in RHA mixture design.

Table 6. Cont.

Study	Theme	Key Finding
Ullah et al. [72]	AI/ML applications	RSM and ANN models optimise ternary RHA-extracted-microsilica concrete; ANN achieves the higher predictive accuracy of the two.
Xu and Lu [50]	AI/ML applications	Hybrid SVR/ANN models with ABC and PSO optimisations improve compressive-strength prediction for RHA concrete.
Reddy et al. [53]	Emerging technologies	Geopolymer concrete with RHA-GGBS replacement evaluated for strength, sulphuric-acid resistance, and cost versus OPC.

Figure 3 presents the resulting PRISMA-style flow diagram for the 2022–2026 Scopus search.

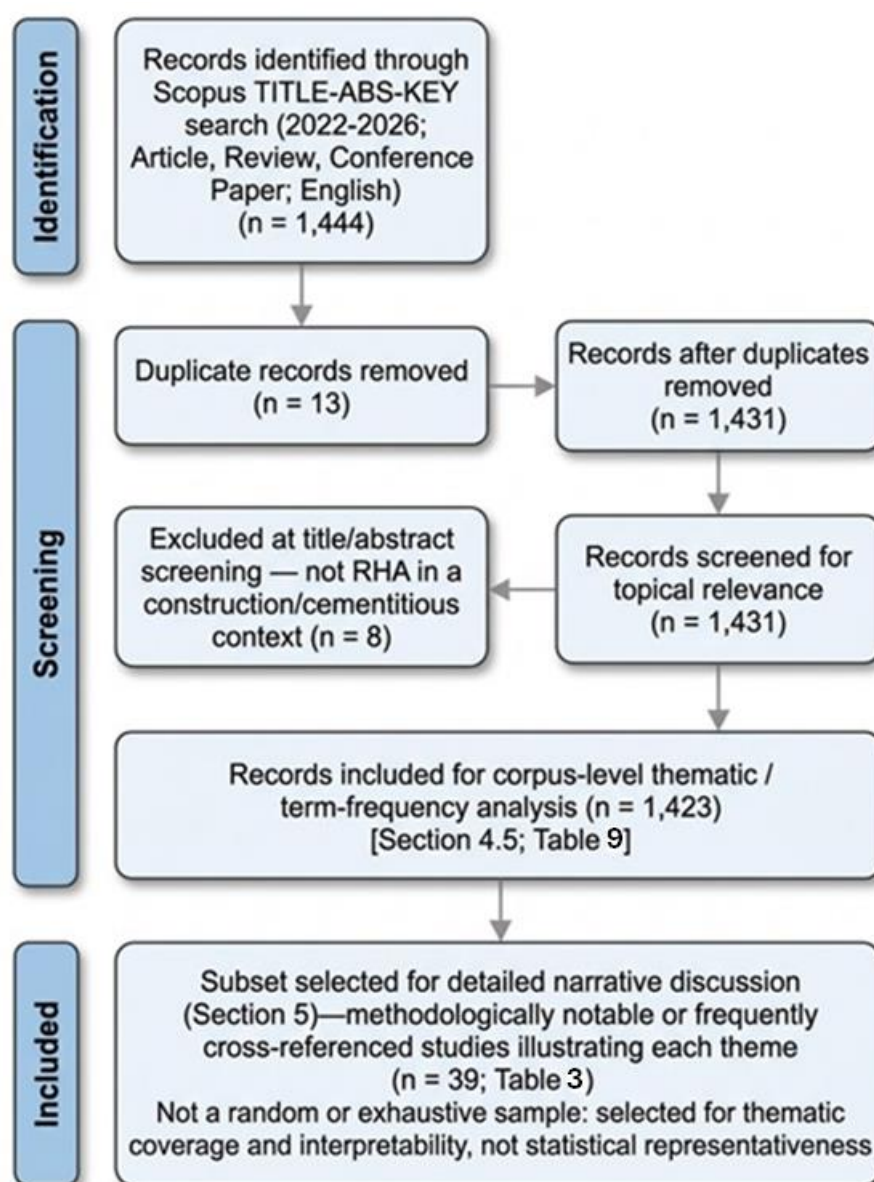


Figure 3. PRISMA-style flow diagram for the 2022–2026 Scopus search (n = 1423 included; n = 39 selected as an illustrative narrative subset, Table 6).

Search Limitations

This search differs from the bibliometric search in Section 3.1 in three respects, both of which are disclosed here as limitations. First, only Scopus was searched; Web of Science access was not available for this stage, so the 2022–2026 corpus may omit records indexed exclusively in Web of Science or other databases, and the figures reported here should be read as a Scopus-specific lower bound rather than an exhaustive cross-database count. Second, thematic classification of the 1423-record corpus (Section 4.5; Table 5) was performed using an automated, keyword-based term-frequency method applied to titles and abstracts, rather than full-text manual coding of every record. This method is fast and fully reproducible, and was validated by manually inspecting samples from each category to check for false positives (for example, an early, broader keyword set for the “policy developments” theme returned 59 records on a single broad token, but manual inspection showed most were false matches on generic phrases such as “standard test method” rather than genuine policy content; the keyword set was tightened accordingly, reducing this category to 4 records, and the same tightening process was applied to all six categories before the counts in Table 5 were finalised). This means Table 5 should be read as a reproducible approximation of thematic prevalence across the corpus, not a human-verified count for every individual record; the $n = 39$ studies discussed narratively in Section 5 and Table 6 were read in full by the authors and are not subject to this limitation. Third, primary screening and data extraction were carried out by a single reviewer, with the co-authors verifying the retained records and extracted data rather than screening independently in duplicate; independent duplicate screening in future work would further reduce the risk of selection and extraction errors. Readers seeking to extend this analysis are encouraged to repeat the search with combined Scopus and Web of Science access and, where feasible, full-text manual screening of the corpus.

Because this study combines a bibliometric analysis with a structured narrative review rather than a meta-analysis of comparable effect estimates, a formal study-level risk-of-bias instrument (e.g., RoB 2 or ROBINS-I) was not applied; such tools are designed for controlled intervention studies and do not transfer directly to the heterogeneous experimental and computational studies reviewed here. Instead, several safeguards were used to limit the influence of low-quality or non-substantive records: eligibility was restricted to peer-reviewed, Scopus-indexed articles, reviews, and conference papers; errata, retracted articles, and notes were identified and reported separately (Table 4) and excluded from substantive interpretation; and the 39 studies discussed in detail (Table 6) were selected partly on methodological quality and read in full. Two limitations follow from this design and are acknowledged in Section Search Limitations: primary screening and data extraction were performed by a single reviewer with subsequent co-author verification rather than by independent duplicate screening, and full-text quality appraisal was not applied to the complete 1423-record corpus.

Figure 4 illustrates the overall research design, showing how the co-authorship and co-occurrence outputs of the bibliometric analysis (Section 4) connect, through the systematic review of recent developments (Section 5), to the synthesis of research gaps, integrated discussion, and the proposed framework reported in Sections 6–8.

The full 1423-record corpus was classified across six cross-cutting themes adapted from the bibliometric clusters and the research gaps identified during screening AI/ML applications, emerging technologies, new methodologies, sustainability issues, industry adoption, and policy developments using the automated term-frequency method described in Section Search Limitations (Table 5). A curated subset of 39 studies, selected to illustrate each theme with concrete, frequently cross-referenced examples, is discussed narratively in Section 5 and listed with theme assignments and key findings in Table 6.

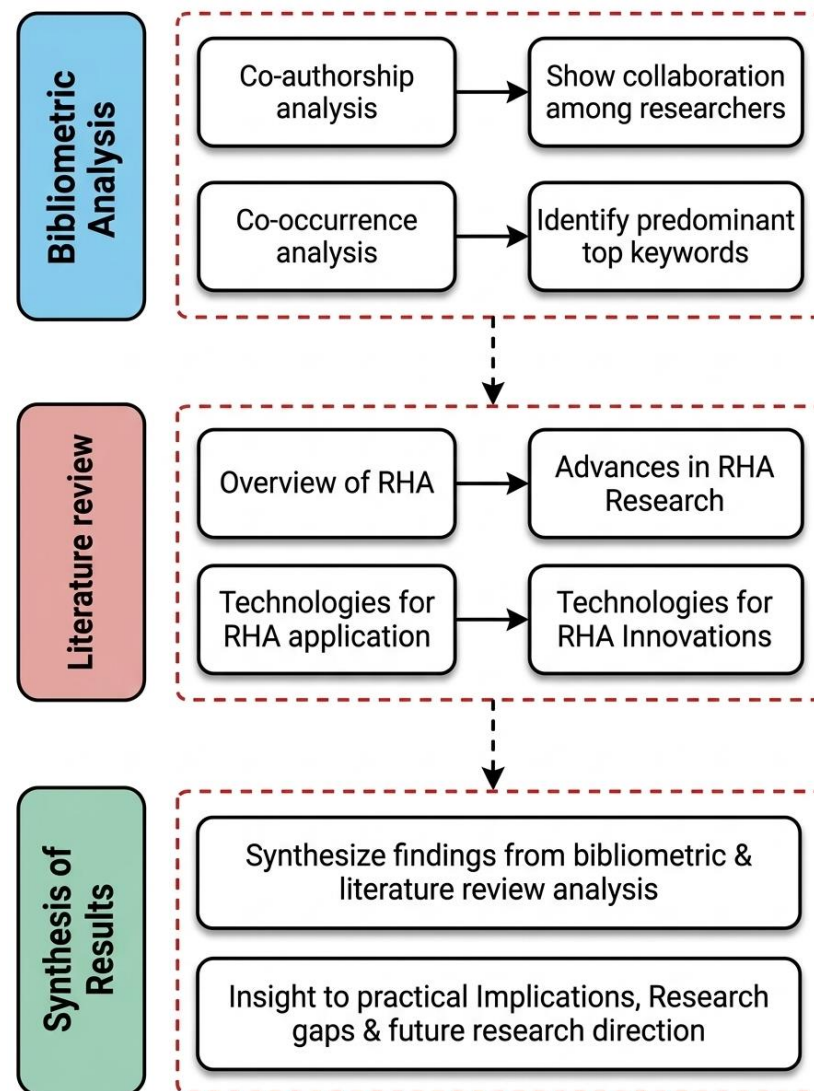


Figure 4. Overall research design illustrating the integration of the bibliometric analysis and the systematic literature review.

4. Bibliometric Results

4.1. Publication Trends, Document Types, and Source Titles

Figure 5 shows the temporal variation in the total number of publications (TP) on RHA-blended concrete (RHAC) research on a yearly basis from 2007 to 2021, as deduced from Scopus. The findings show a steady rise in publications from 2007 to 2021, reflecting the global shift toward sustainability-driven research in construction materials. This growth aligns with international initiatives, such as the UN 2030 Sustainable Development Goals and the European Green Deal, which emphasise carbon-neutral infrastructure [73,74]. The sharp increase after 2017 corresponds to the expansion of open-access databases and advances in characterisation and life-cycle assessment (LCA) techniques, which enhanced visibility and rigour in RHA studies [75]. The increase suggests the field's development from feasibility exploration toward data-based optimisation and performance modelling.

Table 4 shows the various document formats for publications on RHAC in Scopus. The most preferred document types for RHAC studies are articles, conference papers, and reviews, which account for 70.30%, 24.75%, and 2.31% of TP, respectively. It is therefore useful to examine the journal titles or sources in which RHAC research is published.

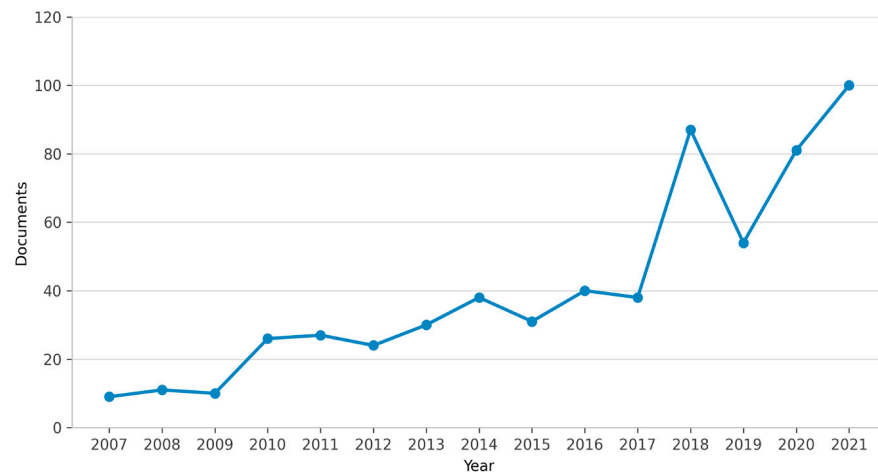


Figure 5. Publication trend in RHAC studies in Scopus, 2007–2021.

Table 7 shows the leading source titles for RHAC publications. The top 10 source titles produced 222 publications, or 36.63% of TP. The leading source title is *Construction and Building Materials (CBM)*, with 90 papers (14.85% of TP). *CBM* prioritises the investigation and innovative use of materials in construction and repair, and its high impact metrics and ranking (impact factor 6.141; ranked 7 of 136 in Civil Engineering) account for its dominance in this field.

Table 7. Source titles for published articles on RHAC (2007–2021).

Source Title	Total Publications (TP)	% of Total Publications
<i>Construction and Building Materials</i>	90	14.85
<i>IOP Conference Series: Materials Science and Engineering</i>	24	3.96
<i>International Journal of Civil Engineering and Technology</i>	18	2.97
<i>Journal of Materials in Civil Engineering</i>	15	2.48
<i>Materials Today: Proceedings</i>	15	2.48
<i>Advanced Materials Research</i>	13	2.15
<i>Journal of Cleaner Production</i>	13	2.15
<i>Lecture Notes in Civil Engineering</i>	13	2.15
<i>Cement and Concrete Composites</i>	11	1.82
<i>IOP Conference Series: Earth and Environmental Science</i>	10	1.65

The second- and third-most influential sources are *IOP Conference Series: Materials Science and Engineering* and the *International Journal of Civil Engineering and Technology*, with 24 (3.96%) and 18 (2.97%) publications, respectively. Other prestigious outlets include the *Journal of Cleaner Production* and *Cement and Concrete Composites*. Five of the top 10 sources are conference proceedings, reflecting researchers' preference for rapid dissemination and peer feedback on empirical findings, a pattern often associated with fields still in their early developmental stages as well as the convenience of conferences for sharing findings among academia, industry, and policymakers.

4.2. Top Authors and Affiliations

The concentration of prolific authors and institutions in Southeast Asia (e.g., Malaysia, Thailand, and India) reflects both geographical and economic realities, as these are among

the world's top rice producers and thus generate abundant RH waste [6,76], encouraged by policies such as Malaysia's National Biofuels Policy and Thailand's Bio-Circular-Green Economy Framework [31]. Co-authorship analysis in VOSviewer (272 of 1586 authors meeting a two-document, two-citation threshold) identifies *Mohd R. Hainin* as the most connected author (total link strength 40), and *Natt Makul* and *Prinya Chindapasirt* as the most prolific by documents (14 and 12, respectively); the top affiliation is *Universiti Tun Hussein Onn Malaysia* (24 publications), with four of the top five affiliations based in Malaysia. High intra-regional co-authorship density alongside weaker links to European and North American institutions points to limited technology transfer and standardisation—a theme that recurs in Section 7. Full author, co-authorship-network, and affiliation figures are provided in Supplementary Materials (Figures S1–S3) to keep this section focused.

4.3. Top Research Funders and Countries

The National Natural Science Foundation of China (NSFC) leads RHA funding with 15 sponsored documents, followed by Brazil's CNPq (14), CAPES (10), and Ministério da Ciência, Tecnologia e Inovação (8), and the Thailand Research Fund (7)—reflecting the incorporation of RHA research into national decarbonisation strategies such as China's "Dual-Carbon" initiative and Brazil's National Policy on Circular Economy [5,77,78]. India, Malaysia, Thailand, China, and Indonesia are the top five research-active countries, consistent with the large RH volumes generated by their rice-milling industries (~0.28 kg RH per kg of rice milled [79]) and supported by policy frameworks such as Malaysia's Bio-Circular-Green Economy Model and India's Waste-to-Wealth Mission [80,81]. Country-level co-authorship analysis shows high interconnectivity (~72.6%), with India leading in total publications (156; 2328 citations) and Malaysia in total link strength (38), and a notable cross-continental cluster linking Hong Kong, China, Cyprus, and Japan—patterns consistent with technology innovation system (TIS) theory and a broader consolidation of South–South innovation links [33,35]. Full funder, country-output, and country-collaboration figures are provided in Supplementary Materials (Figures S4–S6). Overall, the funding and country landscape reflect a shift from locally based waste management toward internationally coordinated circular-economy frameworks, with sustained coordination between funders and standard-setting institutions remaining central to RHA's transition toward zero-carbon construction.

4.4. Top-Cited Publications and Foundational Studies

The analysis of the most-cited publications offers insight into the scientific and intellectual foundations of RHAC research; such heavily referenced studies represent milestones that have driven both applied innovation and academic understanding of sustainable cementitious systems. Table 8 lists the 10 most-cited publications from the 2007–2021 dataset (citation counts updated to 2025), which together have amassed over 5300 citations. The most influential paper, by Ganesan et al. [30], established that an optimal RHA substitution range of 10–30% considerably improves compressive strength while decreasing permeability. Related studies by Chindapasirt and Rukzon [31] and Chindapasirt et al. [81] extended this groundwork by validating the synergistic effects of blending RHA with palm oil fuel ash and fly ash, particularly for improving resistance to chloride and sulphate attack.

Table 8. Top 10 most-cited publications on RHAC (2007–2021).

Reference	Title	Cited by
Ganesan et al. [30]	“Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete”	926
Chindaprasirt and Rukzon [31]	“Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash, and fly ash mortar”	580
Chao-Lung et al. [82]	“Effect of rice husk ash on the strength and durability characteristics of concrete”	543
Saraswathy and Song [28]	“Corrosion performance of rice husk ash blended concrete”	498
Givi et al. [33]	“Assessment of the effects of rice husk ash particle size on strength, water permeability and workability of binary blended concrete”	489
Van Tuan et al. [83]	“Hydration and microstructure of ultra-high-performance concrete incorporating rice husk ash”	487
Zain et al. [35]	“Production of rice husk ash for use in concrete as a supplementary cementitious material”	466
Chindaprasirt et al. [81]	“Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash”	473
Van Tuan et al. [34]	“The study of using rice husk ash to produce ultra-high-performance concrete”	493
Chindaprasirt et al. [29]	“Sulphate resistance of blended cements containing fly ash and rice husk ash”	407

The continued influence of these works underscores their enduring role in elucidating the reaction mechanisms of RHA, particularly the formation of secondary calcium–silicate–hydrate (C–S–H) gel and the refinement of pore structure. Subsequent studies by Givi et al. [33] and Van Tuan et al. [83] advanced the microstructural understanding using XRD, SEM, and TGA, thereby extending RHA’s applicability to ultra-high-performance concrete (UHPC). The citation network in Figure 6, generated using VOSviewer, identifies three influential thematic groups: performance optimisation with emphasis on durability, strength, and permeability; hydration and microstructure analysis exploring reaction mechanisms through TGA, XRD, and SEM; and frameworks for hybrid SCM and sustainability, incorporating RHA with other ashes and eco-friendly binders. These clusters illustrate a field in which conventional materials science increasingly intersects with computational modelling and sustainability metrics. As shown in Section 5, citation surges observed between 2023 and 2025—driven by studies such as Kashem et al. [8] and Alamiery [14]—confirm that this citation landscape is itself shifting toward AI-assisted, circular-economy-oriented research.

The citation landscape of journal sources was likewise assessed via VOSviewer (Figure 7), applying a minimum threshold of five documents and five citations per source. Of 224 indexed journals, 24 met these conditions, forming seven thematic groups of 1–6 nodes each. The largest (red) cluster comprises *MATEC Web of Conferences*, *Advanced Materials Research*, and *Procedia Engineering*, reflecting the strong position of open-access and conference-proceeding platforms in disseminating emerging RHA research. The blue cluster is dominated by *Construction and Building Materials (CBM)*, which has the largest number of published documents (90), total citations (5682), and total link strength (337) among all sources—confirming its status as the central, most influential journal in the field. The prominence of *CBM*, *Cement and Concrete Composites*, and the *Journal of Materials*

in *Civil Engineering* shows that established civil and materials journals have embraced RHA research within the wider discourse on low-carbon concrete and sustainable binders, while clusters comprising *Applied Mechanics and Materials*, *Crystals*, and *Key Engineering Materials* reveal RHA's cross-disciplinary extension into nanotechnology, materials science, and environmental engineering. The presence of the *Journal of Cleaner Production* and the *Journal of Environmental Management* in neighbouring groups reflects growing interest in the circular economy and sustainability dimensions of RHA utilisation. Overall, this network topology suggests an evolution from regionally based, conference-oriented publication (pre-2015) toward peer-reviewed, high-impact, transnational journals in more recent years—consistent with the scientific legitimisation and institutionalisation of RHA research within international advances in green construction.

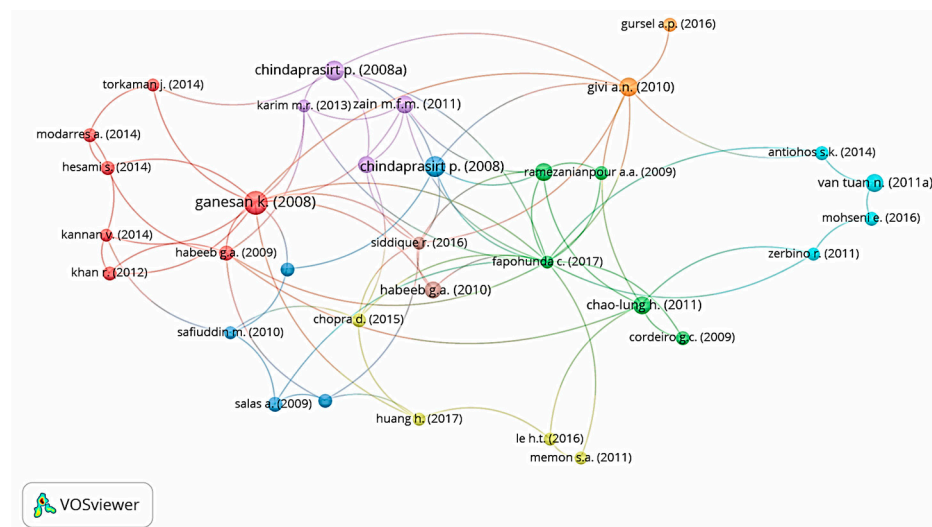


Figure 6. Citation network visualisation of the most-cited publications on RHAC (2007–2021).

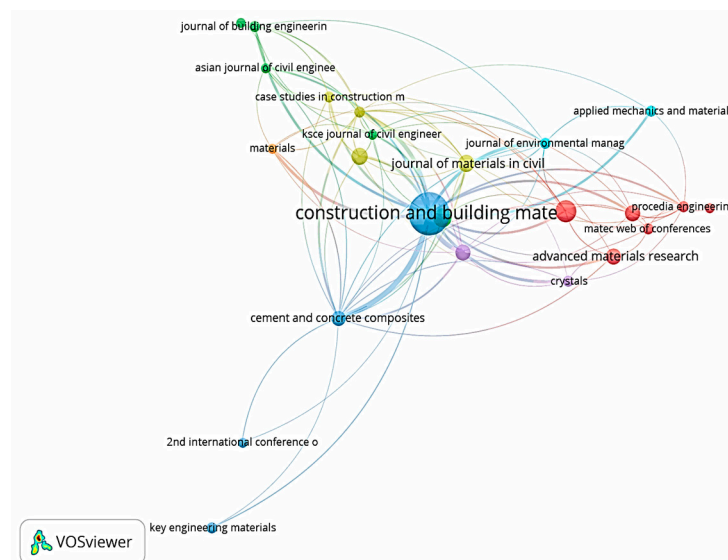


Figure 7. Network visualisation of journal/source citation clusters for RHAC research (2007–2021).

Table 2 summarises 14 of the most influential early studies identified through the bibliometric analysis, illustrating the empirical foundations spanning corrosion performance, sulphate resistance, optimal replacement levels, hydration behaviour, and non-cement binder fabrication that underpin the recent developments reviewed in Section 5.

The combination of high-impact foundational studies (Table 2) and the citation surge observed after 2021 (Figure 6) indicates that, by the close of the bibliometric window, RHA

research was already pivoting toward computational and sustainability-oriented themes. Section 4.5 extends this picture using a real Scopus-derived corpus of literature from 2022 to 2026, before Section 5 discusses a curated set of these studies in narrative depth.

4.5. Corpus-Level Thematic Analysis (2022–2026)

Where Sections 4.1–4.4 characterise the structural evolution of RHA research up to 2021, this section applies the same Scopus-based logic to the period immediately following, using the 1423-record corpus and methodology described in Section 3.2. Table 5 reports the prevalence of six cross-cutting themes across the full corpus, each defined by a reproducible set of keywords (available from the corresponding author on request) and assigned on a multi-label basis (a single record may match more than one theme, so percentages do not sum to 100%). Sustainability issues (29.4% of the corpus) and emerging technologies—principally geopolymers, alkali-activated, and UHPC systems (26.1%) are the two largest cross-cutting themes, followed by AI/ML applications (12.0%) and new production/processing methodologies (8.6%). Industry adoption (0.8%) and policy developments (0.3%) remain marginal, corroborating, with corpus-wide evidence rather than a small illustrative sample, the standardisation and adoption gaps (G3, G6) identified in Section 7. A further 46.9% of records could not be matched to any of the six advanced themes and instead concern baseline mechanical or durability performance, the continuing empirical core of the field, consistent with the foundational studies summarised in Table 2.

Tracking these themes by publication year (Figure 1) shows that sustainability issues grew from 19.9% of annual records in 2022 to 37.0% in 2025, by far the fastest-growing theme in the corpus, while emerging technologies grew more gradually (22.3% to 26.6%) and AI/ML applications remained comparatively flat (9.9% to 13.7%, with a recent uptick). This is an important correction to the framing in earlier drafts of this manuscript, which, based on a small illustrative sample, had characterised machine learning as the single largest and fastest-growing theme in the recent literature; the full corpus instead shows sustainability and life-cycle-oriented research as the dominant growth driver, with computational methods forming a stable but comparatively smaller share of annual output. Both trends are consistent with, and now quantitatively grounded in, the Present-phase narrative developed in Section 6.

5. Recent Developments (2022–2026): A Systematic Literature Review

While the bibliometric analysis establishes the historical evolution and structural dynamics of RHA research up to 2021, it cannot, by design, capture developments published after the data-extraction date. Section 4.5 addressed this at the corpus level, classifying all 1423 Scopus-indexed records from 2022 to 2026 across six cross-cutting themes. This section complements the quantitative picture with a narrative reading of 39 methodologically notable studies from within that corpus, selected to illustrate each theme in technical depth (Tables 5 and 6), tracing how the thematic clusters identified bibliometrically—performance optimisation, sustainability, and emerging computational methods—have continued to develop in the most recent literature.

5.1. Microstructural Mechanisms of RHA

Before reviewing the recent performance and modelling literature in detail, it is useful to set out explicitly the reaction mechanism that underlies essentially all of the findings discussed in this section, since the bibliometric analysis (Section 4.4) shows this mechanism has remained the field's stable scientific core even as research emphasis has shifted toward sustainability and computation. RHA's reactivity originates from its amorphous (non-crystalline) silica content, typically 85–95% SiO₂ by mass when combustion is prop-

erly controlled [5,6]; by contrast, crystalline silica polymorphs are essentially inert under ambient curing conditions. This amorphous silica reacts pozzolanically with calcium hydroxide ($\text{Ca}(\text{OH})_2$, or “CH”) liberated during Portland cement hydration, consuming CH and producing secondary calcium–silicate–hydrate (C–S–H) gel in addition to the primary C–S–H formed from clinker hydration [28,83]. Because secondary C–S–H is more poorly crystalline and finer-grained than primary C–S–H, it preferentially fills capillary pores and refines the pore-size distribution of the cement matrix [6,83].

This pore refinement is most pronounced in the interfacial transition zone (ITZ), the relatively porous, CH-enriched region surrounding aggregate particles, which is normally the weakest and most permeable part of the concrete microstructure. By consuming CH preferentially in this zone and depositing secondary C–S–H within it, RHA densifies the ITZ and reduces the connectivity of the capillary pore network, which is the principal mechanism behind the simultaneous gains in compressive strength, reduced permeability, and improved resistance to chloride and sulphate ingress reported throughout Sections 4.4 and 5.2 [29,30,81,83]. The rate and extent of this reaction are governed primarily by two processing parameters discussed further in Section 5.3: combustion temperature, which determines the proportion of silica retained in amorphous (reactive) versus crystalline (inert) form, and particle fineness, which determines the specific surface area available for pozzolanic reaction. Figure 8 summarises this reaction pathway schematically.

Empirical characterisation studies corroborate this mechanism directly, rather than only by inference. SEM imaging of RHA-blended pastes consistently shows a visibly densified, less porous matrix and a narrower, less defect-prone interfacial transition zone than plain OPC paste, particularly once RHA has been ground to sub-10 μm fineness [6,33]. XRD patterns of RHA-blended systems typically show reduced portlandite ($\text{Ca}(\text{OH})_2$) peak intensity relative to plain OPC at equivalent curing age, consistent with CH consumption during the pozzolanic reaction, while the absence of new crystalline phases beyond those already present in ordinary hydration is itself informative: the bulk of the additional reaction product is the poorly crystalline secondary C–S–H described above, rather than a distinct mineral phase [34,83]. Thermogravimetric analysis (TGA) provides a complementary quantitative check on the same process: the mass-loss step associated with portlandite decomposition (typically in the 400–450 $^{\circ}\text{C}$ range) is measurably smaller in RHA-blended pastes than in plain OPC paste at matched curing age, directly evidencing CH consumption, while bound-water content associated with C–S–H decomposition is correspondingly higher [83]. SEM, XRD, and TGA therefore converge on the same physical picture summarised in Figure 8, providing methodologically independent confirmation of the mechanism rather than a single-technique inference.

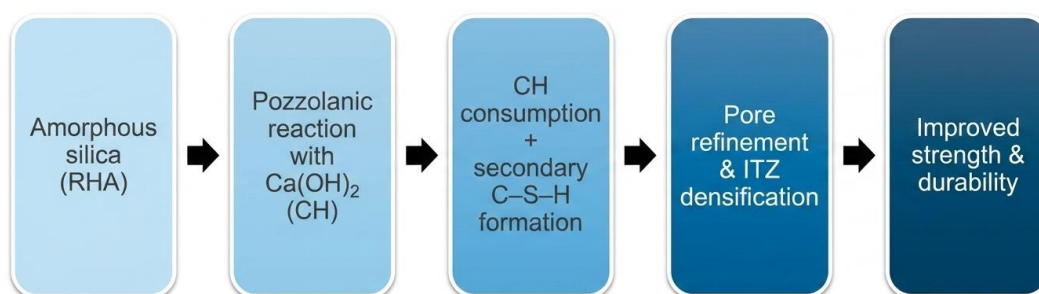


Figure 8. Microstructural reaction pathway of RHA pozzolanic activity, from amorphous silica through CH consumption and secondary C–S–H formation to ITZ densification and pore refinement.

5.2. Performance and Microstructural Advances

Foundational studies established that RHA improves concrete performance primarily through the formation of secondary calcium–silicate–hydrate (C–S–H) gel and the refinement of pore structure [28,83], with controlled processing further enabling its use in ultra-high-performance concrete (UHPC) systems [9]. Building on this established understanding, the literature published since 2022 confirms and extends these mechanisms using more advanced characterisation. Bayaidah et al. [7] reported that ultrafine RHA improves both compressive strength and durability through enhanced particle packing and increased pozzolanic activity, while Kashem et al. [8] showed that, with controlled processing and optimisation of particle fineness, RHA-based systems can be tailored for high-performance applications such as UHPC. These findings indicate that RHA has evolved from a basic SCM into a material capable of meeting advanced engineering performance requirements.

The literature does not converge on a single optimal replacement level: reported optimal levels range from 5% to 20% depending on RHA fineness, burning temperature, and the water–cement mix ratio, and reported strength effects at a given replacement level vary correspondingly across studies. Table 3 synthesises quantitative compressive-strength outcomes reported at specific RHA replacement levels across the screened literature. Rather than implying false precision through a single best-fit curve, the table is presented as a range to make this study-to-study variability explicit, itself an argument for the production-standardisation gap (G1) discussed in Section 7, since variability of this magnitude across studies using nominally similar replacement levels is difficult to reconcile without standardised combustion and fineness protocols.

Despite this variability, the directional pattern for strength is consistent: gains are concentrated in the 5–15% replacement range, with diminishing or mixed returns above approximately 20%, broadly corroborating the 10–30% range identified as safe in the foundational literature (Table 2) while suggesting the lower half of that range is where the most consistent strength gains are reported. Durability behaves differently. A 2025 database-driven synthesis of over 1000 data points drawn from the 1996–2022 literature finds that chloride penetration, porosity, water absorption, and mass loss under sulphuric-acid exposure all continue to decrease, and electrical resistivity and chloride-diffusion resistance continue to improve, up to a database-wide optimum of 30% cement replacement—specifically, chloride penetration falls below 1000 coulombs (the threshold for low chloride permeability) only once replacement exceeds 30% [44]. This means the strength-optimal and durability-optimal replacement levels do not necessarily coincide: a mix optimised purely for 28-day compressive strength (typically 5–15% per Table 3) may leave durability gains on the table that would only be realised at closer to 30% replacement, particularly for chloride-exposed applications such as marine or de-icing-salt environments. This distinction matters for mix design in practice and is a direct, evidence-based reason to specify RHA dosage according to exposure class rather than a single blanket optimum.

5.3. Advances in Production and Processing Techniques

Early studies established that controlled combustion in the 500–800 °C range is essential for preserving amorphous silica content and pozzolanic reactivity [6,17], with pre-treatment methods such as acid washing further improving silica purity [76]. Building on this foundation, recent (2022–2026) research has focused on improving the scalability and consistency of RHA production. Aliyu [5] demonstrated that fluidised-bed combustion and microwave-assisted pyrolysis produce RHA with more uniform particle properties and lower residual carbon content than conventional open-burning methods, directly addressing the variability that has historically constrained large-scale RHA adoption and standardisation.

5.4. Environmental, Economic and Sustainability Implications

Life-cycle assessment (LCA) studies completed toward the end of the bibliometric window already indicated substantial environmental benefits: Ganesan et al. [10] demonstrated that RHA-based concrete reduces overall life-cycle environmental impact, thereby motivating more detailed economic and decarbonisation analyses. Building on this, Ozturk et al. [2] conducted a database-driven evaluation confirming that RHA concrete can simultaneously reduce CO₂ emissions, lower production cost, and maintain eco-strength efficiency across a wide range of mixes. Pham and Tran [1] further situate RHA within circular-economy frameworks, demonstrating how agricultural waste can be valorised into high-value, low-carbon binder systems. Hybrid systems incorporating RHA with other SCMs, such as fly ash, slag, and waste glass powder, have also shown synergistic effects on both mechanical performance and environmental sustainability [11], reinforcing that the future of RHA lies in multi-material and circular construction systems rather than as a standalone material.

5.5. Machine Learning and Data-Driven Modelling

One of the most significant developments to emerge from the post-2021 literature is the application of machine learning (ML) and deep learning (DL) for predictive modelling and optimisation, building on early exploratory work by Ghorbani and Mohammadi [12] and Tran et al. [13], who demonstrated that ML models can capture the complex, nonlinear relationships between RHA mix parameters and concrete performance. Since 2022, this line of work has matured considerably and broadened substantially in scope: of the 39 studies reviewed in this SLR, 16 apply ML or DL methods (Table 5), making this the single largest thematic cluster within this curated illustrative subset. At corpus level, however, machine learning is not the dominant theme: as reported in Section 4.5, AI/ML applications account for 12.0% of the full 1423-record corpus, a smaller share than sustainability issues (29.4%) or emerging technologies (26.1%). The apparent prominence of ML in this section therefore reflects the deliberate, methodologically weighted selection of the 39-study subset rather than the balance of the corpus as a whole. Kashem et al. [8] reported that hybrid ML algorithms can achieve high predictive accuracy for the compressive strength of RHA concrete, while Alamiery [14] introduced symbolic regression models that not only predict performance but also provide interpretable relationships between variables, enhancing understanding and decision-making. Datta [15] further extended this by showing that ML-based optimisation can simultaneously improve mechanical performance and reduce environmental impact, thereby demonstrating the potential of multi-objective optimisation frameworks.

A substantial sub-cluster of this literature focuses on architectural and algorithmic comparisons. Al-Hashem et al. [46] showed that both artificial neural network (ANN) and gene expression programming (GEP) models accurately predict the compressive strength of concrete containing fly ash and RHA, while Li et al. [47] improved on standalone ANN approaches by optimising the network with a reptile search algorithm. Amin et al. [60] compared optimised and hyper-tuned ML models for RHA as an SCM, and Paul et al. [57], Hoang and Nguyen [58], and Karim et al. [59] each extended this work with deep learning and hybrid architectures, the latter using SHAP and partial dependence plot (PDP) analyses to identify which mix variables most strongly drive the predicted compressive strength—an interpretability step that is increasingly expected alongside raw predictive accuracy. Alyami et al. [12] and Al-Shamasneh et al. [13] both benchmarked multiple ML algorithms against one another, with the latter comparing twelve algorithms and finding that support vector regression (SVR), Gaussian process regression (GPR), and NuSVR performed best.

The most recent studies in this cluster move toward ensemble and metaheuristic-optimised architectures. Yang et al. [48] hybridised XGBoost with three metaheuristic optimisers (Northern Goshawk, Arctic Puffin, and Catch Fish Optimisation), finding that cement content remained the most influential predictor of strength. Çağlar [49] combined ensemble learning with multi-objective optimisation to balance compressive-strength prediction against CO₂ and SO₂ emission reduction, while Ullah et al. [72] and Xu and Lu [50] applied response-surface and hybrid SVR/ANN approaches, respectively, to further refine prediction accuracy for RHA and RHA–microsilica concrete systems. Collectively, these studies mark a clear transition from trial-based experimentation to predictive, data-driven material design, in which computational models play a central role in optimising both performance and sustainability outcomes, and in which model interpretability and multi-objective trade-offs are emerging as the field’s next methodological frontier.

To move beyond a narrative account and enable cross-study benchmarking, Table 9 compares the machine learning studies reviewed here on the dimensions most relevant to reproducibility: dataset size and provenance, input variables, validation strategy, reported predictive accuracy, and the interpretability method employed. Three patterns stand out. First, reported dataset sizes span almost an order of magnitude, from a few hundred laboratory records [47,48] to more than 1400 literature-compiled observations [8], and most datasets are assembled from heterogeneous published sources rather than a single controlled campaign, so the high accuracies frequently reported (often $R^2 > 0.93$) partly reflect curated, in-distribution data and may not transfer to field mixes. Second, the input feature sets are strikingly uniform—essentially the same six-to-seven mix-proportion variables (cement, RHA, water, aggregates, superplasticiser, and curing age)—and almost every study targets 28-day compressive strength alone; durability, shrinkage, and life-cycle indicators are largely absent as prediction targets, mirroring the strength-versus-durability divergence noted in Section 5.2. Third, interpretability has shifted from an afterthought to an expected component, with SHAP, partial dependence, and symbolic (GEP/MEP) methods now standard in the most recent studies [12–14] and consistently identifying cement content and the water-to-binder ratio as the dominant predictors. The homogeneity of inputs and targets, combined with reliance on heterogeneously sourced datasets, is itself evidence for the standardisation and open-data gaps discussed in Sections 5.8 and 7.

Table 9. Comparison of representative machine learning studies predicting the compressive strength of RHA concrete (2022–2026).

Study [Ref], Year	ML/DL Method(s)	n	Input Variables	Validation	Best Reported Accuracy	Interpretability/Key Feature
Al-Hashem et al. [46], 2022	ANN; GEP	310 (217/93)	OPC–FA–RHA mix constituents	70:30 hold-out	ANN R^2 0.94/0.88 (tr/ts); GEP R^2 0.80/0.70	Parametric + sensitivity; closed-form GEP equation
Amin et al. [60], 2023	CatBoost, GBM, CNN, GRU	1212	7: cement, water, RHA, fine agg., coarse agg., age, SP	Train/test; 6 error indices	$R^2 > 0.975$ (tr), > 0.925 (ts)	ML-vs-DL family comparison
Li et al. [47], 2023	ANN + reptile-search optimiser (circle mapping)	NR *	RHA-concrete mix constituents	Train/test	Hybrid ANN outperforms standalone ANN	Sensitivity: curing age most influential
Kashem et al. [8], 2024	LGB, XGB, RF + hybrid ML	1404	6: cement, RHA, curing age, water, aggregate, SP	Train/test	High-accuracy hybrid ML (best of set)	Parametric analysis of variable effects
Alyami et al. [12], 2024	RF, LightGBM, ridge, XGBoost	348	5 RHA-concrete mix features	Train/test	LightGBM $R \approx 0.998$ (ts)	SHAP; water/cement identified as controlling

Table 9. Cont.

Study [Ref], Year	ML/DL Method(s)	n	Input Variables	Validation	Best Reported Accuracy	Interpretability/Key Feature
Al-Shamasneh et al. [13], 2025	12 algorithms (SVR, GPR, NuSVR, XGBoost, ETR, DTR, GBR, HGBR, ANN...)	500 + 30 ext.	7: W/B, cement, SP, water, RHA, coarse agg., fine agg.	k-fold/nested CV	SVR, GPR, NuSVR $R^2 > 0.93$; DTR $R^2 < 0.53$	SHAP + permutation importance
Yang et al. [48], 2025	XGBoost + NGO/APO/CFOA vs RF, SVR	291	7 RHA-concrete mix variables	Train/test	APO-XGBoost R^2 0.958, RMSE 3.55 MPa (ts)	Feature importance: cement most influential
Alamiery [14], 2026	GEP, MEP (symbolic regression)	NR *	6: cement, RHA, water, SP, age, fine agg.	Train/test	Interpretable closed-form CS equation	SHAP-based interpretation

* NR = not reported in the source consulted. tr = training, ts = testing. All models predict 28-day compressive strength (CS); none of the studies reviewed targets a durability or life-cycle indicator as its prediction output, itself a research gap identified in Section 7.

5.6. Digital Twins and Emerging Construction Technologies

Beyond machine learning, digital technologies are beginning to influence RHA research, although this remains the least developed of the themes reviewed here. Digital twin technology, which enables real-time simulation and monitoring of structural performance, has been proposed in the broader concrete and infrastructure literature as a means of supporting predictive maintenance and life-cycle optimisation; however, RHA-specific applications of digital twins were not identified in the screened literature, representing a clear research opportunity rather than an established finding. More concretely, recent studies have explored the integration of RHA into other emerging construction technologies: Behfarnia et al. [18] demonstrated the potential of natural pozzolan-based geopolymers incorporating RHA for high-temperature-resistant applications, while Rashidi et al. [19] examined the microstructural performance of alkali-activated ferro-silicomanganese slag systems relevant to RHA-blended alkali-activated binders. These applications remain comparatively underexplored compared with conventional OPC–RHA systems, underscoring the integration of RHA into digital construction and advanced manufacturing processes as a key frontier for the field, which is discussed further in the proposed framework in Section 8.

5.7. Comparative Performance with Other Supplementary Cementitious Materials

Many recent studies have assessed RHA against other SCMs—fly ash (FA), silica fume (SF), ground granulated blast-furnace slag (GGBFS), and metakaolin (MK)—which differ in reactivity, composition, and performance [84,85]. While SF offers ultrafine particle size and high pozzolanic reactivity, FA and GGBFS primarily provide latent hydraulic characteristics, and MK offers strong pozzolanic activity at low replacement levels. RHA is differentiated by its biogenic origin, high amorphous silica content, and comparatively low environmental footprint. Ternary blends incorporating SF, RHA, and GGBFS have shown superior performance: Gupta et al. [86] reported a 6–13% increase in compressive strength for RHA–SF–GGBFS ternary binders, while Bameri et al. [11] found pronounced improvements in sulphate resistance and surface resistivity for comparable eco-friendly blends incorporating waste glass powder. In alkali-activated systems, RHA-relevant binders have shown microstructural improvements comparable to those in slag-based systems [11] and high-temperature stability comparable to that of natural pozzolan-derived geopolymers [18]. Bayaidah et al. [7] further showed that ultrafine RHA improves both strength and durability while reducing carbon emissions and reusing agricultural waste, consistent with global sustainability goals. Table 10 quantifies these comparisons directly, addressing the question of why an industry stakeholder might choose RHA over an established

SCM: on raw strength contribution alone, RHA is not the strongest performer of the five—metakaolin and fly ash report larger gains at their respective optimal replacement levels (Table 10) but RHA offers the most direct waste-valorisation and circular-economy case of the group, drawing on an agricultural by-product stream of roughly 70 million tonnes per year [87] that would otherwise be burned or landfilled. The trade-off, made explicit in the final column of Table 10, is that this advantage is currently offset by weaker production standardisation than fly ash, silica fume, or GGBFS, each of which benefits from decades of industrial-scale processing and ASTM/EN specification coverage that RHA largely lacks (Section 7, G1).

Table 10. Quantitative comparison of RHA with other established supplementary cementitious materials.

SCM	Typical Replacement	Strength Effect	Durability Contribution	CO ₂ /Sustainability	Cost & Availability
Fly Ash (FA)	10–20%	Up to +30% at 28 days [87]	Reduces permeability; +15–20% long-term durability gain [43]	Ranked highest of 27 SCMs assessed [25]; cuts cement GWP 50–90% [25]	Lowest cost; ~750 Mt/yr, declining with coal-plant closures [25]
Silica Fume (SF)	5–15%	Substantial gains at 5–15%, very high reactivity	Very effective at controlling RAC durability and chloride ingress [15]	Energy-intensive by-product; high reactivity offsets footprint	Higher cost; ~1.5 Mt/yr, silicon-producing regions only [25]
GGBFS	30–55%	~+25% at 30% replacement [87]	Strong long-term durability and sulphate resistance [25]	Ranked 2nd–3rd of established SCMs [25]	Moderate cost; tied to steel output, ~300–360 Mt/yr [25]
Metakaolin (MK)	~10%	Up to +40% at 10% replacement [87]	Refines pore structure; reduces permeability	Ranked lowest of the five on combined criteria [25]	Higher cost; engineered, less regionally abundant [25]
Rice Husk Ash (RHA)	5–20%	+9–29%, study-dependent (Table 3)	Improves chloride/sulphate resistance via ITZ densification (Section 5.1; Table 2)	Strongest circular-economy case; ~70 Mt/yr generated [87]; least standardised	Low cost where milling is concentrated; processing consistency is the barrier (Section 5.8)

5.8. Standardisation and Industrial-Adoption Barriers

Section 4.5 and Table 6 show that industry adoption and policy are, by a wide margin, the most marginal themes in the 2022–2026 corpus (0.8% and 0.3% of 1423 records, respectively), and Table 10 identifies standardisation as the specific axis on which RHA lags its established competitors. It is useful to be concrete about what this gap consists of. RHA is not explicitly covered by the two standards that govern the established SCMs compared in Table 10: ASTM C618, which specifies requirements for coal fly ash and raw or calcined natural pozzolans (Class N), and EN 197-1, which specifies the composition of common cements incorporating recognised mineral additions. Some studies test RHA against the ASTM C618 Class N loss-on-ignition and fineness criteria as a practical proxy, but a recent synthesis of SCM standardisation notes that RHA does not, strictly, meet the standard’s definition of a natural pozzolan, since it originates from an annually cultivated crop residue rather than a geological deposit [88]. The consequence is concrete: in a recent standardisation-focused study of blended Portland cements in Spain, one of the European Union’s largest rice producers, the authors note explicitly that RHA use as a mineral addition in cement manufacture is not currently permitted under EN 197-1, despite demonstrating technical feasibility as a pozzolanic material since the 1970s, and propose provisional designations (e.g., CEM II/A-H, CEM II/B-(H-V), using “H” to denote RHA

in blended cements) precisely because no standard category yet exists [89]. This is the regulatory mechanism underlying gap G1 and G6 (Table 5): without a recognised standard designation, specifiers, ready-mix producers, and certification bodies have no compliance pathway for RHA-blended cement, regardless of its demonstrated laboratory performance.

This regulatory gap compounds, rather than merely accompanies, the production variability discussed in Section 5.3: because no standard specifies acceptable combustion temperature, fineness, or amorphous silica thresholds for RHA destined for cement use, individual producers and researchers each define their own quality criteria, which is part of why Table 3 shows such wide variation in reported strength outcomes at nominally similar replacement levels. By contrast, fly ash and GGBFS benefit from decades of standardised classification (e.g., ASTM C618 Class F/C for fly ash) that allows a specifier to write “20% Class F fly ash” into a project specification with a well-defined compliance test. Commercial-scale RHA use to date is correspondingly limited to contexts where a producer controls the full chain from rice mill to concrete batching plant, or to jurisdictions and project types (e.g., low-rise rural construction in rice-producing regions) where formal standard compliance is less strictly enforced; large-scale, standards-governed infrastructure projects remain largely inaccessible to RHA under current regulatory frameworks.

Quality control is the practical mechanism through which this standardisation gap is currently, imperfectly, managed in the absence of a governing standard. Where RHA is used commercially today, producers typically substitute project-specific acceptance testing for loss-on-ignition, fineness (Blaine or sieve residue), and a strength activity index test against a reference mortar, modelled on the testing battery in ASTM C618 already mandated for fly ash and natural pozzolans, for the standard designation that does not yet exist. This works at small scale, where a single producer–batcher relationship allows direct verification of every batch, but it does not substitute for a standard at the scale Table 10 implies fly ash, GGBFS, and silica fume currently operate at: without a published specification, a ready-mix producer sourcing RHA from multiple rice mills, or a national highway authority specifying RHA for a public infrastructure contract, has no independent, third-party-auditable basis for batch acceptance or rejection. This is the immediate, practical reason the production-standardisation gap (G1) and the industrial-adoption gap (G6, Table 5) are mutually reinforcing rather than independent: standardisation would not only legitimise RHA-blended cement under EN 197-1 or ASTM C618 but would also furnish the quality-control test methods that currently have to be improvised project by project.

Closing this gap, via either an RHA-specific designation in a future revision of ASTM C618 or EN 197-1, or a recognised national standard in major rice-producing countries, is therefore not a secondary recommendation but a precondition for the industrial-policy adoption tier (Tier 5) of the framework proposed in Section 8.

5.9. Synthesis: From Material Optimisation to Intelligent Systems

Read together, the studies reviewed in this section describe a coherent three-phase progression in RHA research. The first phase (Past, 2007–2015) was dominated by experimental validation and feasibility studies establishing basic mechanical and pozzolanic performance. The second phase (Past, 2016–2021) shifted toward microstructural and durability optimisation, supported by more advanced characterisation techniques (XRD, SEM, TGA) and the first life-cycle assessments. The third phase (Present, 2022–2026) is defined by data-driven modelling and digital integration, in which machine learning, multi-objective optimisation, and early digital and alkali-activated applications increasingly complement, rather than replace, the experimental foundations of the first two phases. This progression demonstrates that RHA is no longer simply a supplementary material but is evolving into a component of sustainable, intelligent, and digitally integrated construction systems.

Table 5 and Table 6 summarise, respectively, the individual studies reviewed in this section and the six thematic categories used to organise them, providing a transparent basis for the integrated discussion in Section 6.

6. Integrated Discussion

Figure 9 synthesises the evidence reviewed across Sections 4 and 5 into a single causal pathway, from RHA processing decisions through the resulting microstructure to concrete performance and, ultimately, sustainability outcomes. The dashed feedback loop reflects the standardisation and quality-control gap identified in Section 5.8: without standardised processing and quality control, the performance and sustainability gains shown in the diagram cannot be reliably or consistently realised at industrial scale, which is precisely why that gap is treated throughout this discussion as a precondition for, rather than a parallel track to, further materials science progress.

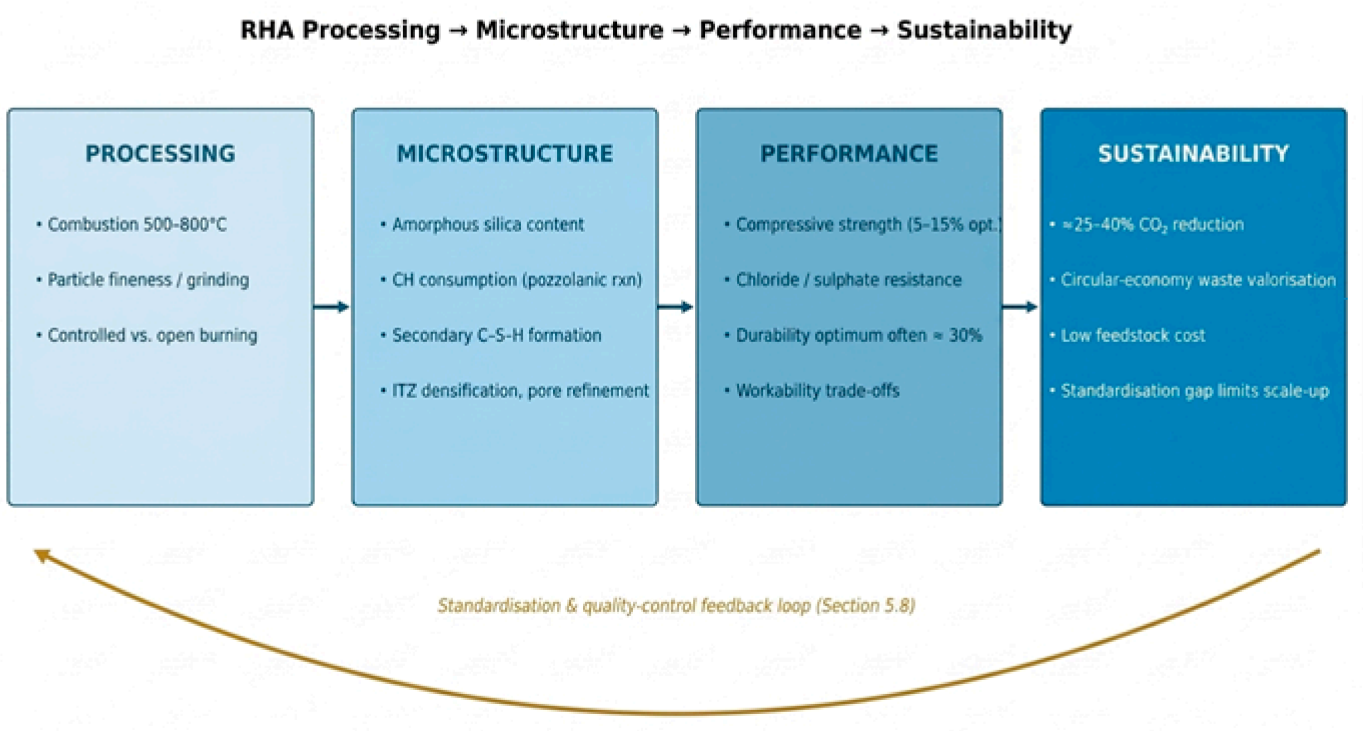


Figure 9. Integrated synthesis of the RHA processing–microstructure–performance–sustainability pathway, with the standardisation and quality-control feedback loop (Section 5.8) shown as the binding constraint on industrial-scale realisation.

6.1. Connecting the Bibliometric and Literature Evidence: A Past–Present–Future Narrative

The value of the hybrid BA-SLR design lies in explicitly connecting what the bibliometric analysis shows about the structure and history of the field with what the systematic review shows about its most recent scientific content. The bibliometric analysis identified sustainability, durability, and microstructural performance as the dominant themes shaping RHA research up to 2021, supported by a citation network still centred on foundational strength- and permeability-focused studies (Section 4.4). The systematic review of the 2022–2026 literature shows that this foundation has since been extended, rather than replaced: post-2021 studies increasingly combine the same underlying pozzolanic and microstructural mechanisms with AI-driven optimisation, more detailed life-cycle accounting, and early exploration of geopolymer and alkali-activated applications (Section 5). Read together, the two strands of evidence describe a coherent Past–Present–Future trajectory: a Past (2007–2015) of experimental feasibility, a Present (2016–2025, spanning the end of

the BA window and the SLR period) in which microstructural optimisation has matured into data-driven and sustainability-integrated design, and an emerging Future, addressed directly in Sections 7 and 8, in which standardisation, large-scale validation, and digital integration must be resolved before RHA can move from laboratory-scale innovation to mainstream industrial practice.

6.2. Research Trends and Growth (Past)

The bibliometric analysis shows a marked rise in RHA publications after 2017, coinciding with global climate initiatives and rapid developments in digital-materials research more broadly. Asian nations, led by Malaysia, India, China, and Thailand, dominate publication output and cross-institutional partnerships, reflecting both the accessibility of rice husk feedstock and national strategies promoting the sustainable valorisation of biomass (Section 4.3). Co-citation and co-authorship networks reveal robust intra-regional collaboration, though improved technology transfer and international standardisation remain needed (Section 4.2). The growing trend toward cross-border collaboration, particularly among South–South nations, highlights the diffusion of sustainable material innovation across emerging economies.

6.3. Technological and Methodological Advances (Present)

The combined evidence base traces a clear methodological trajectory. Feasibility studies in the early 2010s identified optimal substitution levels and the combustion parameters critical to pozzolanic reactivity (Table 2). The following period brought substantial advances in microstructural characterisation via XRD, SEM, and EDX—deepening understanding of RHA's hydration mechanisms and nanostructure (Section 4.4). As detailed in Section 5, this trajectory has, since 2022, extended further into machine learning, deep learning, and life-cycle assessment, transforming RHA optimisation from an experimental practice into an increasingly data-driven, predictive science. Combustion of rice husk within the 600–800 °C range remains the accepted standard for producing highly reactive, amorphous, silica-dense ash, while emerging synthesis techniques such as fluidised-bed combustion and microwave-assisted pyrolysis (Section 5.3) are improving the reproducibility, stability, and scalability of RHA production. Combined with hybrid ML–LCA modelling (Sections 5.4 and 5.5), these developments lay the groundwork for more complete sustainability optimisation, positioning RHA as a keystone material within next-generation, data-informed cementitious systems.

6.4. Environmental, Economic, and Practical Implications

RHA utilisation in cementitious systems delivers a dual benefit of waste valorisation and carbon reduction: substituting 10–30% of cement with RHA lowers the CO₂ footprint of concrete by an amount that is best expressed as a range rather than a single figure. A database evaluation by Ozturk et al. [2] reports carbon footprint reductions on the order of 25% at optimal replacement, and a more recent database synthesis finds reductions of up to roughly 40% where RHA is combined with other pozzolans such as fly ash or metakaolin [44]; these authors emphasise, however, that the achievable reduction is strongly conditional on the life-cycle system boundary and, in particular, on the combustion method used to produce the ash (controlled or energy-recovery combustion versus open burning), the replacement ratio, and transport distance, so that a fixed percentage cannot be quoted independently of these assumptions [2,10]. Within these caveats, the reduction is achieved while maintaining or improving mechanical performance and resistance to chloride and sulphate attack [29,30,81] a meaningful contribution given that cement production is a major global source of greenhouse gas emissions. These durability gains are particularly valuable in HPC and UHPC applications in industrial, marine, and

otherwise aggressive environments, where corrosion protection and long service life are critical [28,77,83]. Economically, RHA is most competitive in regions where rice-milling waste and decentralised biomass-calcination infrastructure are already abundant, reinforcing the link between agricultural-waste management and circular-economy-oriented infrastructure development. The growing combination of machine learning, deep learning, and digital twin-oriented thinking (Sections 5.5 and 5.6) is further transforming how RHA-based concretes are designed and managed, enabling predictive mix optimisation and life-cycle forecasting that reduce experimental cost and improve precision [12–15]. Taken together, these developments strengthen RHA's role as a key enabler of the transition toward circular, sustainable, and intelligent construction practice, a role formalised in the framework proposed in Section 8.

7. Research Gaps and Future Directions

Although the merits of RHA as an SCM are well-established, several unresolved challenges continue to limit its widespread use in sustainable construction. The most pressing issue is the absence of consistent production procedures, particularly regarding fineness optimisation, amorphous silica content, and combustion temperature; the lack of reliable processing standards leads to inconsistent performance and reactivity, limiting comparability and industrial confidence across studies. This gap could be addressed through internationally calibrated certification frameworks that ensure consistent quality and reproducibility in RHA utilisation. A second key challenge concerns the optimal replacement level under diverse service conditions, including HPC, UHPC, and chloride-, sulphate-, or acid-rich environments. While laboratory studies consistently demonstrate the effectiveness of 10–30% replacement, the absence of large-scale validation and long-term field data prevents decisive performance benchmarking; future work should therefore prioritise multi-regional pilot schemes and extended durability evaluations to close the gap between controlled experimental results and real-world performance.

The scientific progression documented in Section 5 presents not only a gap but also an opportunity. The growing use of machine learning, deep learning, and digital twin-oriented approaches offers substantial potential for predictive optimisation and real-time monitoring of RHA-based concretes; however, progress remains constrained by data fragmentation and the absence of open-access digital datasets. Shared, standardised datasets and AI-ready data infrastructure would materially improve the accuracy of predictive modelling and accelerate RHA optimisation in practice. Equally important is the still-limited application of life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) across regions; expanding these frameworks would support a more holistic accounting of the socio-economic and environmental benefits of RHA utilisation, thereby directly supporting circular-economy research objectives.

As summarised in Table 11, the identified research gaps are supported by both the bibliometric analysis and the systematic literature review. The BA highlights fragmented collaboration networks, regional research clustering, and limited thematic centrality of sustainability and digitalisation, while the SLR confirms persistent challenges related to RHA variability, techno-economic uncertainty, and insufficient industrial-scale implementation.

The exploration of RHA in emerging construction technologies remains at an early stage. Beyond the alkali-activated, 3D-printed, and hybrid SCM systems already discussed (Sections 5.6 and 5.7), several materials science-specific directions stand out as particularly promising and currently underexplored for RHA specifically, even where they are more mature for other SCMs: nano-engineered RHA (surface-functionalised or nano-silica-blended RHA, paralleling recent nanomaterial-blended cement composite research [25]); deeper integration of RHA into UHPC mix design beyond the binary blends

reviewed in Section 5.2; RHA-specific geopolymer and alkali-activated binder systems, which remain comparatively underexplored relative to fly ash- and slag-based geopolymers; hybrid multi-SCM systems combining RHA with fly ash, GGBFS, or metakaolin to offset RHA's standardisation weaknesses with the more mature supply chains of its established counterparts (Table 10); AI-assisted mix design extending the predictive modelling reviewed in Section 5.5 toward real-time, plant-level process control; 3D-printed and additive manufacturing concrete incorporating RHA, building on early feasibility work [68]; and carbon-negative or net-negative concrete formulations that combine RHA with carbonation-curing or CO₂-mineralisation technologies, a combination not yet reported for RHA specifically in the screened literature. Future research should focus on integrating AI and other digital tools into process control, mix design, and performance forecasting for these next-generation applications. Figure 10 illustrates the research gaps and corresponding future directions for RHAC research.

Table 11. Mapping of identified research gaps to evidence from the BA and SLR.

No.	Research Gap	Evidence from BA	Evidence from SLR
G1	Lack of standardised RHA production and quality control	Fragmented collaboration networks and absence of dominant standard-setting institutions indicate limited harmonisation.	High variability in reported RHA properties due to inconsistent combustion temperature, fineness, and silica content.
G2	Limited large-scale and long-term field validation	Publication output dominated by laboratory-scale studies with minimal practice-oriented research.	Majority of studies focus on short-term mechanical and durability tests with limited field performance data.
G3	Underrepresentation of RHA in emerging construction technologies	Low frequency of keywords related to 3D printing, alkali-activated binders, and additive manufacturing.	Only a small number of studies explore RHA in geopolymers and digital construction applications.
G4	Weak integration of experimental and computational modelling	ML/DL-related publications appear mainly after 2021 and remain peripheral in thematic clustering.	Computational models often rely on isolated datasets with limited experimental or life-cycle coupling.
G5	Insufficient life-cycle and techno-economic assessment	Sustainability- and LCA-related keywords appear less frequently than strength and durability metrics.	Economic feasibility and regional cost analyses are inconsistently reported across studies.
G6	Limited international standardisation and technology transfer	Strong regional research clusters with weak intercontinental collaboration links.	Literature highlights barriers to industrial adoption due to lack of global specifications and guidelines.

As shown in Figure 10, these issues could be effectively resolved through large-scale field validation, standardisation, comprehensive sustainability assessment, and digital innovation—steps that would be fundamental to the transition of RHA from laboratory research to mainstream industrial practice. Achieving these aims would strengthen RHA's role in sustainable construction and accelerate the transition toward circular and carbon-neutral building practices worldwide. Section 8 proposes an integrated framework intended to operationalise this transition.

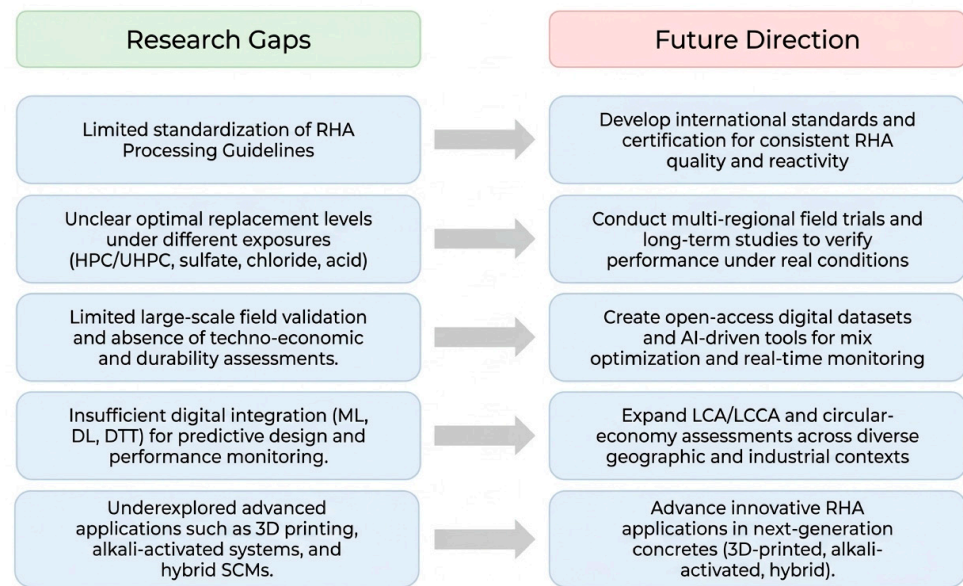


Figure 10. Research gaps and future directions for RHAC research.

8. Proposed Framework

The research gaps identified in Section 7 point not only to missing knowledge but also to a missing structure for connecting RHA's technical, environmental, and computational dimensions into a single research and adoption agenda. Rather than concluding with a generic call for “further research”, this section proposes an integrated framework, illustrated in Figure 11, that synthesises the structural insights of the bibliometric analysis with the technical and methodological insights of the systematic review into a five-tier research agenda and adoption pathway. The framework is intended to function simultaneously as a conceptual model of how RHA research has evolved, an adoption framework for industry stakeholders, and a research agenda for closing the gaps summarised in Table 11.

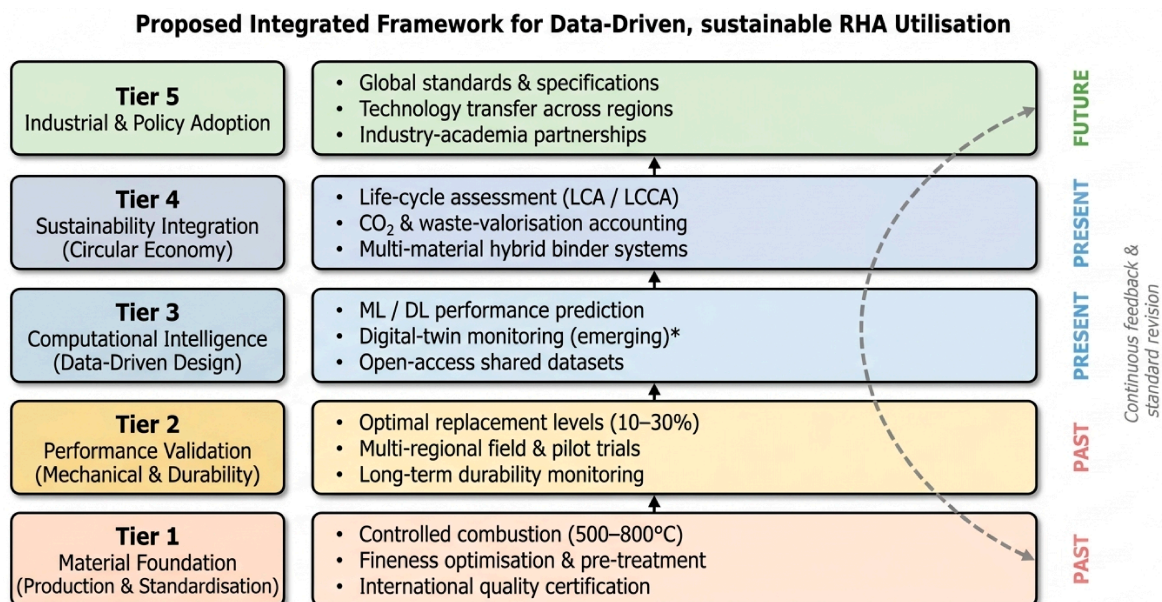


Figure 11. Proposed integrated framework for data-driven, sustainable RHA utilisation in concrete.

Table 12 makes the basis for this structure explicit, tracing each tier back to specific bibliometric evidence (Section 4), the SLR themes summarised in Table 5, and the research

gap(s) it is intended to close (Table 11). This traceability is the framework’s main justification: rather than an arbitrary five-stage model, each tier is anchored to a distinct, identifiable body of evidence, and the “evidentiary status” column makes clear which components are already well supported and which remain comparatively aspirational.

Table 12. Traceability of proposed framework tiers to bibliometric evidence, SLR themes, and research gaps.

Tier	Bibliometric Evidence (Section 4)	SLR Theme(s) (Table 5)	Gap(s) Addressed (Table 11)	Evidentiary Status
1. Material Foundation	Foundational, highly cited studies on combustion temperature and fineness (Section 4.4; Table 2)	New methodologies	G1	Established
2. Performance Validation	Top-cited publications on strength, permeability and durability (Table 8); citation network centred on performance themes (Figure 6)	Emerging technologies (ultrafine RHA, comparative SCM performance)	G2	Established
3. Computational Intelligence	Citation surge in ML-related literature after 2021 (Figure 6; Section 4.4)	AI/ML applications	G4	Emerging (ML); aspirational (digital twins) *
4. Sustainability Integration	Sustainability/LCA keywords underrepresented relative to strength and durability metrics (Section 4.1)	Sustainability issues	G5	Emerging
5. Industrial & Policy Adoption	Fragmented international collaboration with weak intercontinental links (Section 4.3; Supplementary Figure S6)	Policy developments; Industry adoption	G3, G6	Aspirational

* As noted in Section 5.6, no RHA-specific digital twin application was identified in the screened literature; this component of Tier 3 is presented as a proposed future capability rather than a documented trend, and should not be read as evidence of current adoption.

Tier 1, Material Foundation, addresses the standardisation gap (G1) by consolidating existing evidence on combustion temperature, fineness, and pre-treatment (Section 5.3) into internationally recognised production and quality-certification protocols. Tier 2, Performance Validation, responds to the large-scale and field-validation gap (G2) by extending the well-established 10–30% replacement evidence base (Section 4.4; Table 2) through multi-regional pilot schemes and long-term durability monitoring. Tier 3, Computational Intelligence, builds directly on the machine learning and data-driven modelling developments reviewed in Section 5.5—which are already evidenced by multiple post-2021 studies—and targets the weak experimental–computational integration gap (G4) through open-access datasets; digital twin-enabled monitoring is also nested within this tier as a forward-looking capability, but, as Table 12 indicates, it remains aspirational rather than evidenced (Section 5.6). Tier 4, Sustainability Integration, addresses the techno-economic and life-cycle assessment gap (G5) by extending the LCA and circular-economy evidence reviewed in Section 5.4 to a wider range of geographic and industrial contexts. Tier 5, Industrial and Policy Adoption, responds to the standardisation and technology-transfer gap (G6), and to the comparatively static policy landscape identified in Table 5, by linking the regional valorisation policies discussed in Section 4.3 to global specifications and cross-regional technology transfer.

The dashed feedback loop in Figure 11 reflects that this is not a one-directional pipeline: performance data generated in Tier 2 should continuously inform the production standards of Tier 1, just as Tier 5 adoption experience should feed back into the certification and standardisation work of Tier 1, mirroring the iterative, practice-informed model of technology diffusion described by innovation diffusion theory (Section 2). As Table 12 summarises, Tiers 1 and 2 are already substantially evidenced by the existing literature (the Past and

Present strands of Section 6.1); Tier 3 is unevenly evidenced, with machine learning well supported but digital twins aspirational; Tier 4 is emerging, with a growing but still comparatively thin evidence base; and Tier 5 remains the most aspirational, representing the clearest priority for the next generation of RHA research and the most direct route from laboratory-scale innovation to industrial-scale, low-carbon construction practice.

9. Conclusions

This study provides a comprehensive and integrated assessment of research on rice husk ash (RHA) in concrete through the combined application of a bibliometric analysis (2007–2021) and a systematic literature review of recent developments (2022–2026). The findings demonstrate that RHA has evolved from a conventional supplementary cementitious material into a strategically important component of sustainable, low-carbon construction systems. The bibliometric analysis reveals a clear progression in research activity, expanding global collaboration, and the emergence of new thematic areas related to sustainability, modelling, and digital technologies. Interpreted alongside the systematic review findings through the integrated Past–Present–Future narrative developed in Section 6, these trends confirm a structured evolution of the field from early experimental validation to microstructural optimisation and, more recently, toward data-driven and computational approaches, indicating a broader transition from material-level investigation to system-level innovation.

The systematic review further establishes that RHA significantly enhances the mechanical and durability performance of concrete through improved pozzolanic reactivity, microstructural densification, and pore refinement, while its capacity to reduce clinker content and associated CO₂ emissions positions it as a key enabler of circular-economy strategies. Recent studies reinforce this role by demonstrating the integration of RHA into hybrid material systems and life-cycle-based optimisation frameworks. A central contribution of this study is the identification of a paradigm shift toward intelligent, data-driven material systems: the growing adoption of machine learning and digital technologies in RHA research marks a transition from traditional experimental approaches toward predictive modelling and optimisation, enabling more efficient material design, improved performance prediction, and enhanced scalability.

Despite these advances, critical challenges remain, including the lack of standardised production methods, limited large-scale and long-term field validation, and fragmentation of the datasets used in machine learning models; the integration of RHA into emerging technologies such as 3D printing, digital twins, and smart infrastructure systems likewise remains underexplored (Section 7). To address these challenges directly, this study proposes a five-tier integrated framework (Section 8) that links material standardisation, performance validation, computational intelligence, sustainability integration, and industrial-policy adoption into a single, iterative research and adoption agenda. Overall, the integration of BA and SLR demonstrates the effectiveness of a hybrid analytical approach in capturing both the structural evolution and the scientific advancement of RHA research; by linking quantitative research trends with qualitative scientific insight and a forward-looking framework, this study offers a methodological template that may be applied to the study of other emerging materials in sustainable construction research.

For industry practitioners, the practical implications of this study are direct. Specifiers and ready-mix producers in rice-producing regions can expect the most reliable performance gains from RHA in the 5–15% replacement range (Table 3; Section 5.1), where pozzolanic reactivity, ITZ densification, and workability are best balanced; replacement beyond approximately 20% should be approached cautiously pending further standardisation. Table 10 provides a direct, quantitative basis for comparing RHA with fly ash, silica fume,

GGBFS, and metakaolin when selecting an SCM for a given project, rather than requiring practitioners to assemble such a comparison from the primary literature themselves. The standardisation gap identified in Section 5.8 is the single most consequential barrier to commercial-scale adoption identified in this study: until RHA receives explicit treatment under ASTM C618 or an equivalent national or regional standard, or until provisional designations such as those proposed for EN 197-1 [89] are formally adopted, large-scale, standards-governed use will remain the exception rather than the rule, regardless of further laboratory-scale performance evidence. Policymakers and standards bodies in major rice-producing countries are therefore positioned to unlock industrial-scale adoption more directly than further materials science research alone, by prioritising RHA-specific standardisation (Tier 1 of the framework in Section 8) ahead of, or in parallel with, the computational and sustainability-integration work that has dominated the recent literature (Section 4.5).

Looking forward, future research should prioritise the development of standardised, shared datasets, large-scale field validation studies, and the deeper integration of digital technologies into RHA-based systems, guided by the framework proposed in Section 8. In particular, the combination of artificial intelligence, life-cycle assessment, and advanced manufacturing techniques presents significant opportunities to advance RHA as a scalable, sustainable, and intelligent construction material, supporting the broader transition toward low-carbon, resilient, and digitally enabled construction systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/jcs10080381/s1>, Figure S1: Top 5 most prolific authors in RHAC research (2007–2021). Corresponds to Figure 1 referenced in Section 4.2 of the main text; Figure S2: Network visualisation map for co-authorship on RHAC research (2007–2021). Corresponds to Figure 8 referenced in Section 4.2 of the main text; Figure S3: Top 5 most prolific affiliations in RHAC research (2007–2021). Corresponds to Figure 6 referenced in Section 4.2 of the main text; Figure S4: Top 5 funding organisations for RHAC research (2007–2021). Corresponds to Figure 7 referenced in Section 4.3 of the main text; Figure S5: RHAC research output (2007–2021) in the top 5 most active countries. Corresponds to Figure 10 referenced in Section 4.3 of the main text; Figure S6: Network visualisation map for country-based collaboration on RHAC research (2007–2021). Corresponds to Figure 11 referenced in Section 4.3 of the main text; PRISMA checklist (Reference [90] is cited in the Supplementary Materials).

Author Contributions: A.I.: Methodology, formal analysis, interpretation of results, writing—review and editing, validation. A.S.M.: Conceptualisation, methodology, literature search, data curation, formal analysis, visualisation, writing the original draft, project administration, correspondence, writing, review and editing. R.H.: Investigation, methodology, interpretation of findings, writing—review and editing, validation. M.A.A.A.: Formal analysis, methodology, critical review of the manuscript, validation, writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Statement: The bibliometric dataset (2007–2021) was retrieved from Scopus, and the corpus-level dataset (2022–2026; $n = 1423$) was retrieved from Scopus on 22 June 2026 using the search strategy reported in Sections 3.1 and 3.2; both are available from the corresponding author upon reasonable request. Raw Scopus export files and the screening/classification scripts used in Sections 4.5 and 5.1 are available from the corresponding author upon request.

Acknowledgments: The authors also acknowledge the support of A’Sharqiyah University (ASU) and the International College of Engineering and Management (ICEM), for facilitating this research. During the preparation of this work, the authors used an AI-based large language model (scite.ai, Individual Tier) to assist with the literature search. After using this tool, the authors reviewed,

verified, and edited the content as necessary and takes full responsibility for the content of the published article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Amran, M.; Fediuk, R.; Murali, G.; Vatin, N.; Karelina, M.; Ozbakkaloglu, T.; Mishra, J. Rice husk ash-based concrete composites: A critical review of their properties and applications. *Crystals* **2021**, *11*, 168. [\[CrossRef\]](#)
2. Ozturk, E.; Ince, C.; Derogar, S.; Ball, R. Factors affecting the CO₂ emissions, cost efficiency and eco-strength efficiency of concrete containing rice husk ash: A database study. *Constr. Build. Mater.* **2022**, *326*, 126905. [\[CrossRef\]](#)
3. Hamad, M.A. Production of ultrahigh-performance concrete with low energy consumption and carbon footprint using supplementary cementitious materials instead of silica fume: A review. *Energies* **2021**, *14*, 8291. [\[CrossRef\]](#)
4. Prasara-A, J.; Gheewala, S.H. Sustainable utilization of rice husk ash from power plants: A review. *J. Clean. Prod.* **2017**, *167*, 1020–1028. [\[CrossRef\]](#)
5. Aliyu, A.S. Synthesis and characterization of rice husk and palm fruit bunch silica: Compositional, structural, thermal analyses. *Biomass Convers. Biorefin.* **2024**, *15*, 3533–3544. [\[CrossRef\]](#)
6. Cordeiro, G.C.; Filho, R.D.T.; Tavares, L.M.; Fairbairn, E.D.M.R.; Hempel, S. Influence of particle size and specific surface area on the pozzolanic activity of residual rice husk ash. *Cem. Concr. Compos.* **2011**, *33*, 529–534. [\[CrossRef\]](#)
7. Nassar, R.U.D.; Room, S. Strength, Durability, and Microstructural Characteristics of Binary Concrete Mixes Developed with Ultrafine Rice Husk Ash as Partial Substitution of Binder. *Civ. Eng. Archit.* **2025**, *13*, 595–611. [\[CrossRef\]](#)
8. Kashem, A.; Karim, R.; Das, P.; Datta, S.D.; Alharthai, M. Compressive strength prediction of sustainable concrete incorporating rice husk ash (RHA) using hybrid machine learning algorithms and parametric analyses. *Case Stud. Constr. Mater.* **2024**, *20*, e03030. [\[CrossRef\]](#)
9. Kang, S.H.; Hong, S.G.; Moon, J. The use of rice husk ash as reactive filler in ultrahigh performance concrete. *Cem. Concr. Res.* **2019**, *115*, 389–400. [\[CrossRef\]](#)
10. Fernando, S.; Gunasekara, C.; Law, D.W.; Nasvi, M.C.M.; Setunge, S.; Dissanayake, R. Life cycle assessment and cost analysis of fly ash–rice husk ash blended alkali-activated concrete. *J. Environ. Manag.* **2021**, *295*, 113140. [\[CrossRef\]](#)
11. Bameri, M.; Rashidi, S.; Mohammadhasani, M.; Maghsoudi, M.; Madani, H.; Rahmani, F. Evaluation of Mechanical and Durability Properties of Eco-Friendly Concrete Containing Silica Fume, Waste Glass Powder, and GGBFS. *Adv. Civ. Eng.* **2022**, *2022*, 2730391. [\[CrossRef\]](#)
12. Alyami, M.; Nassar, R.-U.; Khan, M.; Hammad, A.W.; Alabduljabbar, H.; Nawaz, R.; Fawad, M.; Gamil, Y. Estimating compressive strength of concrete containing rice husk ash using interpretable machine learning-based models. *Case Stud. Constr. Mater.* **2024**, *20*, e02901. [\[CrossRef\]](#)
13. Al-Shamasneh, A.A.R.; Kewalramani, M.; Mahmoodzadeh, A.; Alghamdi, A.; Alnahas, J.; Ghazouani, N.; Sulaiman, M. Forecasting compressive strength of concrete containing rice husk ash using various machine learning algorithms. *Sci. Rep.* **2025**, *15*, 39162. [\[CrossRef\]](#) [\[PubMed\]](#)
14. George, S.; Hussain, S.A.; Alamiery, A.A.; Pathan, M.G.; Sabihuddin, S.; Thakur, N.; Smerat, A. Enhancing compressive strength prediction of sustainable concrete using MEP and GEP models with SHAP-based interpretation. *Asian J. Civ. Eng.* **2026**, *27*, 245–262.
15. Li, Q.; Song, Z. Prediction of compressive strength of rice husk ash concrete based on stacking ensemble learning model. *J. Clean. Prod.* **2023**, *382*, 135279. [\[CrossRef\]](#)
16. Khan, R.; Jabbar, A.; Ahmad, I.; Khan, W.; Khan, A.N.; Mirza, J. Reduction in environmental problems using rice-husk ash in concrete. *Constr. Build. Mater.* **2012**, *30*, 360–365. [\[CrossRef\]](#)
17. Pode, R. Potential applications of rice husk ash waste from rice husk biomass power plant. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1468–1485. [\[CrossRef\]](#)
18. Pachideh, G.; Gholhaki, M.; Aljenabi, A.; Rezaifar, O. Compressive strength ratios of concretes containing pozzolans under elevated temperatures. *Heliyon* **2024**, *10*, e26932. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Rashidi, S.; Bameri, M.; Madani, H.; Maghsoudi, M. Multiscale Assessment of Microstructural Features Effects on the Performance of Alkali-Activated Ferro-Silicomanganese Slag. *J. Build. Eng.* **2024**, *93*, 109207. [\[CrossRef\]](#)
20. Ajibade, S.-S.M.; Zaidi, A.; Bekun, F.V.; Adediran, A.O.; Bassey, M.A. A research landscape bibliometric analysis on climate change for last decades: Evidence from applications of machine learning. *Heliyon* **2023**, *9*, e20297. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [\[CrossRef\]](#)
22. Thomas, B.S. Green concrete partially comprised of rice husk ash as a supplementary cementitious material—A comprehensive review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3913–3923. [\[CrossRef\]](#)

23. Siddika, A.; Al Mamun, M.A.; Alyousef, R.; Mohammadhosseini, H. State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. *J. King Saud. Univ.-Eng. Sci.* **2021**, *33*, 294–307. [[CrossRef](#)]
24. Amin, M.N.; Ahmad, W.; Khan, K.; Sayed, M.M. Mapping research knowledge on rice husk ash application in concrete: A scientometric review. *Materials* **2022**, *15*, 3431. [[CrossRef](#)] [[PubMed](#)]
25. Samarajeewa, P.; Buddika, S.; Yapa, H.; Gunasekara, C.; Law, D.W. Rice husk ash and nanomaterial-blended cement composites: A review. *Environ. Sci. Pollut. Res.* **2026**, *33*, 717–735. [[CrossRef](#)]
26. ASTM C618-22; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2022.
27. BS EN 197-1:2011; Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements. British Standards Institution: London, UK, 2011.
28. Saraswathy, V.; Song, H.W. Corrosion performance of rice husk ash blended concrete. *Constr. Build. Mater.* **2007**, *21*, 1779–1784. [[CrossRef](#)]
29. Chindaprasirt, P.; Kanchanda, P.; Sathonsaowaphak, A.; Cao, H.T. Sulfate resistance of blended cements containing fly ash and rice husk ash. *Constr. Build. Mater.* **2007**, *21*, 1356–1361. [[CrossRef](#)]
30. Ganesan, K.; Rajagopal, K.; Thangavel, K. Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Constr. Build. Mater.* **2008**, *22*, 1675–1683. [[CrossRef](#)]
31. Chindaprasirt, P.; Rukzon, S. Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash and fly ash mortar. *Constr. Build. Mater.* **2008**, *22*, 1601–1606. [[CrossRef](#)]
32. Habeeb, G.A.; Fayyadh, M.M. Rice Husk Ash concrete: The effect of RHA average particle size on mechanical properties and drying shrinkage. *Aust. J. Basic Appl. Sci.* **2009**, *3*, 1616–1622.
33. Givi, A.N.; Rashid, S.A.; Aziz, F.N.A.; Salleh, M.A.M. Assessment of the effects of rice husk ash particle size on strength, water permeability and workability of binary blended concrete. *Constr. Build. Mater.* **2010**, *24*, 2145–2150. [[CrossRef](#)]
34. Van Tuan, N.; Ye, G.; Van Breugel, K.; Fraaij, A.L.A.; Bui, D.D. The study of using rice husk ash to produce ultra high performance concrete. *Constr. Build. Mater.* **2011**, *25*, 2030–2035. [[CrossRef](#)]
35. Zain, M.F.M.; Islam, M.N.; Mahmud, F.; Jamil, M. Production of rice husk ash for use in concrete as a supplementary cementitious material. *Constr. Build. Mater.* **2011**, *25*, 798–805. [[CrossRef](#)]
36. Karim, M.R.; Zain, M.F.M.; Jamil, M.; Lai, F.C. Fabrication of a non-cement binder using slag, palm oil fuel ash and rice husk ash with sodium hydroxide. *Constr. Build. Mater.* **2013**, *49*, 894–902. [[CrossRef](#)]
37. Chopra, D.; Siddique, R. Strength, permeability and microstructure of self-compacting concrete containing rice husk ash. *Biosyst. Eng.* **2015**, *130*, 72–80. [[CrossRef](#)]
38. Bie, R.S.; Song, X.F.; Liu, Q.Q.; Ji, X.Y.; Chen, P. Studies on effects of burning conditions and rice husk ash (RHA) blending amount on the mechanical behavior of cement. *Cem. Concr. Compos.* **2015**, *55*, 162–168. [[CrossRef](#)]
39. Zareei, S.A.; Ameri, F.; Dorostkar, F.; Ahmadi, M. Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case Stud. Constr. Mater.* **2017**, *7*, 73–81. [[CrossRef](#)]
40. Khankhaje, E.; Jang, H.; Kim, J.; Rafieizonooz, M. Utilizing rice husk ash as cement replacement in pervious concrete: A review. *Results Mater.* **2025**, *22*, 100675. [[CrossRef](#)]
41. Mohamed, A.M.; Tayeh, B.A.; Majeed, S.S.; Aisheh, Y.I.A.; Ariffin, M.A.B.M. Optimizing rice husk ash for ultra-high-performance concrete: A comprehensive review of mechanical properties, durability, and environmental benefits. *Rev. Adv. Mater. Sci.* **2025**, *64*, 20250146. [[CrossRef](#)]
42. Yin, X.; Rahman, M.M.; Sun, Y.; Zhao, Y.; Wang, J. Sustainable soil–cement composites with rice husk ash and silica fume: A review of performance and environmental benefits. *Materials* **2025**, *18*, 2880. [[CrossRef](#)] [[PubMed](#)]
43. Al-Alwan, A.A.K.; Al-Bazoon, M.; Mussa, F.I.; Alalwan, H.A.; Shadhar, M.H.; Mohammed, M.M.; Mohammed, M.F. The impact of using rice husk ash as a replacement material in concrete: An experimental study. *J. King Saud. Univ.-Eng. Sci.* **2022**, *36*, 249–255.
44. Öztürk, E.; Ince, C.; Borgianni, Y.; Derogar, S.; Forster, A.M.; Ball, R.J. Enhancing concrete durability and resource efficiency through rice husk ash incorporation: A data-driven approach. *Sustainability* **2025**, *17*, 9382. [[CrossRef](#)]
45. van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [[PubMed](#)]
46. Al-Hashem, M.N.; Amin, M.N.; Raheel, M.; Khan, K.; Alkadhim, H.A.; Imran, M.; Ullah, S.; Iqbal, M. Predicting the Compressive Strength of Concrete Containing Fly Ash and Rice Husk Ash Using ANN and GEP Models. *Materials* **2022**, *15*, 7713. [[CrossRef](#)] [[PubMed](#)]
47. Li, C.; Mei, X.; Dias, D.; Cui, Z.; Zhou, J. Compressive Strength Prediction of Rice Husk Ash Concrete Using a Hybrid Artificial Neural Network Model. *Materials* **2023**, *16*, 3135. [[CrossRef](#)] [[PubMed](#)]
48. Yang, W.; Ji, Y.; Zhou, S.; Ji, L.; Lei, Y.; Wang, M. Towards Sustainable Construction: Hybrid Prediction Modeling for Compressive Strength of Rice Husk Ash Concrete. *Designs* **2025**, *9*, 141. [[CrossRef](#)]

49. Çağlar, H. Sustainable mixture design of rice husk ash cement based concrete: Performance optimization through data driven modeling and multi objective analysis. *Sci. Rep.* **2026**, *16*, 18108. [[CrossRef](#)] [[PubMed](#)]
50. Xu, X.; Lu, J. Prediction of Compressive Strength of Rice Husk Ash Mix Concrete Using Support Vector Regression and Artificial Neural Networks Integrated with Artificial Bee Colony and Particle Swarm Optimization Algorithms. *J. Nat. Fibers* **2026**, *23*, 2625776. [[CrossRef](#)]
51. Fernando, S.; Gunasekara, C.; Law, D.W.; Nasvi, M.C.M.; Setunge, S. Assessment of long term durability properties of blended fly ash-rice husk ash alkali activated concrete. *Constr. Build. Mater.* **2023**, *369*, 130449. [[CrossRef](#)]
52. Cárdenas-Pulido, J.; Ramirez, F.; Velandia, D.F.; Reyes, J.C.; Carrillo, J.; Aperador, W. Engineering behavior of ambient-cured geopolymer concrete activated by an alternative silicate from rice husk ash. *Eur. J. Environ. Civ. Eng.* **2023**, *27*, 4435–4465. [[CrossRef](#)]
53. Reddy, N.G.; Karikatti, V.B.; Pratap, B.; Patil, S.V.; Serjun, V.Z. Strength and cost analysis of geopolymer concrete using rice husk ash and GGBS as sustainable cement alternatives. *Sci. Rep.* **2026**, *16*, 12922. [[CrossRef](#)] [[PubMed](#)]
54. Ullah, M.F.; Tang, H.; Ullah, A.; Khan, K. Synergistic effects of rice husk ash and extracted microsilica on the performance of high-strength concrete. *Sci. Rep.* **2025**, *15*, 41274. [[CrossRef](#)] [[PubMed](#)]
55. Tien, N.H. Computational materials design for low-carbon binders. *Cem. Concr. Res.* **2025**, *178*, 107211.
56. Miah, M.J.; Miah, M.S.; Mughal, H.; Hasan, N.M.S. Mitigating Environmental Impact Through the Use of Rice Husk Ash in Sustainable Concrete: Experimental Study, Numerical Modelling, and Optimisation. *Materials* **2025**, *18*, 3298. [[CrossRef](#)] [[PubMed](#)]
57. Paul, S.; Das, P.; Kashem, A.; Islam, N. Sustainable of rice husk ash concrete compressive strength prediction utilizing artificial intelligence techniques. *Asian J. Civ. Eng.* **2024**, *25*, 1349–1364. [[CrossRef](#)]
58. Hoang, N.D.; Nguyen, Q.L. Compressive strength estimation of rice husk ash-blended high-strength concrete using diffGrad-optimized deep learning approach. *Multiscale Multidiscip. Model. Exp. Des.* **2024**, *7*, 1953–1973.
59. Karim, R.; Islam, M.H.; Datta, S.D.; Kashem, A. Synergistic effects of supplementary cementitious materials and compressive strength prediction of concrete using machine learning algorithms with SHAP and PDP analyses. *Case Stud. Constr. Mater.* **2024**, *20*, e02828. [[CrossRef](#)]
60. Amin, M.N.; Khan, K.; Arab, A.M.A.; Farooq, F.; Eldin, S.M.; Javed, M.F. Prediction of sustainable concrete utilizing rice husk ash (RHA) as supplementary cementitious material (SCM): Optimization and hyper-tuning. *J. Mater. Res. Technol.* **2023**, *25*, 1495–1523. [[CrossRef](#)]
61. Hamada, H.M.; Al-Attar, A.; Beddu, S.; Askar, M.K.; Yousif, S.T.; Majdi, A. Impact of rice husk ash on geopolymer concrete: A literature review and future directions. *Case Stud. Constr. Mater.* **2025**, *22*, e04476. [[CrossRef](#)]
62. Hasan, N.M.S.; Sobuz, H.R.; Khan, M.H.; Mim, N.J.; Meraz, M.; Datta, S.D.; Rana, J.; Saha, A.; Akid, A.S.M.; Mehedi, T.; et al. Integration of rice husk ash as supplementary cementitious material in the production of sustainable high-strength concrete. *Materials* **2022**, *15*, 8171. [[CrossRef](#)] [[PubMed](#)]
63. Jing, Y.; Lee, J.C.; Moon, W.C.; Ng, J.L.; Yew, M.K.; Jin, Y. Durability and environmental evaluation of rice husk ash sustainable concrete containing carbon nanotubes. *Sci. Rep.* **2025**, *15*, 4352. [[CrossRef](#)] [[PubMed](#)]
64. Wang, H.; Pang, J.; Zou, J.; Xu, Y.; Han, J. Erosion degradation analysis of rice husk ash-rubber-fiber concrete under hygrothermal environment. *Sci. Rep.* **2024**, *14*, 3608. [[CrossRef](#)]
65. Verma, P.; Goldar, D.; Md, D.; Singh, S.K. Effect of rice husk ash on the properties and performance of geopolymer concrete. *Int. J. Civ. Eng.* **2024**, *11*, 11–22. [[CrossRef](#)]
66. Indumathi, M.; Nakkeeran, G.; Roy, D.; Gupta, S.K.; Alaneme, G.U. Innovative approaches to sustainable construction: A detailed study of rice husk ash as an eco-friendly substitute in cement production. *Discov. Appl. Sci.* **2024**, *6*, 597. [[CrossRef](#)]
67. de Araujo, A.F.; Caldas, L.R.; Hasparyk, N.P.; Filho, R.D.T. Low-Carbon Bio-Concretes with Wood, Bamboo, and Rice Husk Aggregates: Life Cycle Assessment for Sustainable Wall Systems. *Sustainability* **2025**, *17*, 2176. [[CrossRef](#)]
68. Samad, N.A.I.A.; Abdullah, S.R.; Ibrahim, M.; Shahidan, S.; Ismail, N. Initial properties of 3D printing concrete using Rice Husk Ash (RHA) as Partial Cement Replacement. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1022*, 012055. [[CrossRef](#)]
69. Hidayat, T.; Setyawan, N. Hoerudin, Semi Pilot Scale Study on Production of Silica from Rice Husk Ash. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1172*, 012049. [[CrossRef](#)]
70. Endale, S.A.; Taffese, W.Z.; Vo, D.-H.; Yehualaw, M.D. Rice Husk Ash in Concrete. *Sustainability* **2023**, *15*, 137. [[CrossRef](#)]
71. Li, Y.; Jia, H.; Li, S. Impact of Rice Husk Ash Properties on Concrete Strength: Experimental and Machine Learning Study. *Adv. Civ. Eng.* **2025**, *2025*, 1812998. [[CrossRef](#)]
72. Ullah, M.F.; Tang, H.; Ullah, A.; Ahmad, S.; Alzlfawi, A.; Ahmad, M.; Tóth, Z. Modeling and optimization of sustainable ternary concrete incorporating rice husk ash and extracted micro silica. *Sci. Rep.* **2026**, *16*, 5063. [[CrossRef](#)] [[PubMed](#)]
73. Koppmann, R.; Von Czapiewski, K.; Reid, J. A review of biomass burning emissions, part I: Gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. *Atmos. Chem. Phys. Discuss.* **2005**, *5*, 10455–10516. [[CrossRef](#)]
74. Nagrale, S.; Hajare, H.; Modak, P.R. Utilization of rice husk ash. *Carbon* **2012**, *2*, 42.

75. CBS. *Biomass Burning and Environmental Pollution: The Case of Rice Husk Management*; Central Bureau of Statistics: New Delhi, India, 2022.
76. Singh, B. *Rice Husk Ash in Waste and Supplementary Cementitious Materials in Concrete*; Elsevier BV: Amsterdam, The Netherlands, 2018; pp. 417–460.
77. Huang, H.; Gao, X.; Wang, H.; Ye, H. Influence of rice husk ash on strength and permeability of ultrahigh performance concrete. *Constr. Build. Mater.* **2017**, *149*, 621–628. [[CrossRef](#)]
78. Jamil, M.; Kaish, A.; Raman, S.N.; Zain, M.F.M. Pozzolanic contribution of rice husk ash in cementitious system. *Constr. Build. Mater.* **2013**, *47*, 588–593. [[CrossRef](#)]
79. IRRI. Rice Husks. Rice By-Products 2020. Available online: <https://bit.ly/3i1fCkz> (accessed on 11 January 2020).
80. Wong, S.L.; Nyakuma, B.B.; Wong, K.Y.; Lee, C.T.; Lee, T.H.; Lee, C.H. Microplastics and nanoplastics in global food webs: A bibliometric analysis (2009–2019). *Mar. Pollut. Bull.* **2020**, *158*, 111432. [[CrossRef](#)] [[PubMed](#)]
81. Chindaprasirt, P.; Rukzon, S.; Sirivivatnanon, V. Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. *Constr. Build. Mater.* **2008**, *22*, 932–938. [[CrossRef](#)]
82. Chao-Lung, H.; Anh-Tuan, B.L.; Chun-Tsun, C. Effect of rice husk ash on the strength and durability characteristics of concrete. *Constr. Build. Mater.* **2011**, *25*, 3768–3772. [[CrossRef](#)]
83. Van Tuan, N.; Ye, G.; Van Breugel, K.; Copuroglu, O. Hydration and microstructure of ultra high performance concrete incorporating rice husk ash. *Cem. Concr. Res.* **2011**, *41*, 1104–1111. [[CrossRef](#)]
84. Mehta, A.; Siddique, R. Sustainable geopolymer concrete using ground granulated blast furnace slag and rice husk ash: Strength and permeability properties. *J. Clean. Prod.* **2018**, *205*, 49–57. [[CrossRef](#)]
85. Xu, W.; Lo, T.Y.; Wang, W.; Ouyang, D.; Wang, P.; Xing, F. Pozzolanic reactivity of silica fume and ground rice husk ash as reactive silica in a cementitious system: A comparative study. *Materials* **2016**, *9*, 146. [[CrossRef](#)] [[PubMed](#)]
86. Gupta, M.; Raj, R.; Sahu, A.K. Effect of Rice Husk Ash, Silica Fume & GGBFS on Compressive Strength of Performance-Based Concrete. *Mater. Today Proc.* **2021**, *43*, 1391–1396.
87. Akintayo, B.D.; Babatunde, O.M.; Akintayo, D.C.; Olanrewaju, O.A. Transforming industrial waste into low-carbon cement: A multi-criteria assessment of supplementary cementitious materials for sustainable concrete design. *Recycling* **2025**, *10*, 211. [[CrossRef](#)]
88. National Academies of Sciences, Engineering, and Medicine. *Use of Supplementary Cementitious Materials for Concrete*; The National Academies Press: Washington, DC, USA, 2025. [[CrossRef](#)] [[PubMed](#)]
89. Ordoñez, L.M.; Borrachero, M.V.; Monzó, J.; Soriano, L.; Payá, J. Binary and ternary blended Portland cements containing different types of rice husk ash. *Materials* **2024**, *17*, 2923. [[CrossRef](#)] [[PubMed](#)]
90. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.