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RICE-BY PRODUCTS POTENTIAL AS PRECURSORS IN GEOPOLYMER CONCRETE: A REVIEW AND ITS BENEFICIAL USE OF STUDIES

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Abstract. Rice serves as a primary staple in many Asian nations, generating significant straw residue during cultivation. Improper disposal or burning of this residue not only contributes to environmental hazards, such as greenhouse gas emissions, but also leads to the loss of a valuable agricultural by-product for farmers. Harnessing rice straw for construction purposes presents an opportunity to advance sustainable practices and provide a clean energy solution to address India's increasing energy demands. Nevertheless, ensuring the sustainability of rice straw ash in geopolymer production requires thoughtful evaluation within the current agricultural landscape of India. Although rice straw is carbon-neutral, concerns about its environmental impact throughout the entire process, from cultivation to transportation, have been raised. This review evaluates methods and materials for partially replacing rice straw in construction for environmental sustainability. It also discusses mathematical models for predicting mechanical properties and examines the potential of rice straw ash and other materials as replacements in construction.

Keywords: rice straw ash, construction industries, artificial neural network, geopolymer materials.

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1. Introduction

In recent years, there has been a significant and unwavering increase in the production and utilization of high-strength concrete (HSC) within the construction industry, particularly in the context of contemporary construction projects. This surge in popularity and adoption of HSC underscores its pivotal role in modern construction work, where the demand for advanced and resilient building materials is paramount. The burgeoning trend toward incorporating high-strength concrete can be attributed to its exceptional mechanical properties, durability, and ability to meet the stringent requirements of diverse construction applications. As the construction industry continues to evolve, the widespread use of HSC represents a transformative shift towards employing cutting-edge materials that offer enhanced strength and performance, ultimately contributing to the construction of more robust and enduring structures. A significant portion of industrial solid waste, as well as waste incineration bottom ash, is often haphazardly deposited, leading to adverse effects on both land resources and the environment. Repurposing these wastes for the preparation of geopolymers emerges as a viable solution. Geopolymer materials, fly ash and rice straw ash, derived from recycled industrial waste, exhibit remarkable properties, not only effectively adsorbing heavy metals, dyes, and other pollutants but also holding substantial potential for broader societal development as depicted in Figure 1. Beyond their pollution mitigation capabilities, geopolymer materials offer diverse applications, extending the scope of their utilization. It introduces valuable insights into the properties and potential applications of geopolymer materials, highlighting their significant role in sustainable waste management and environmental protection (Cong & Cheng, 2021).

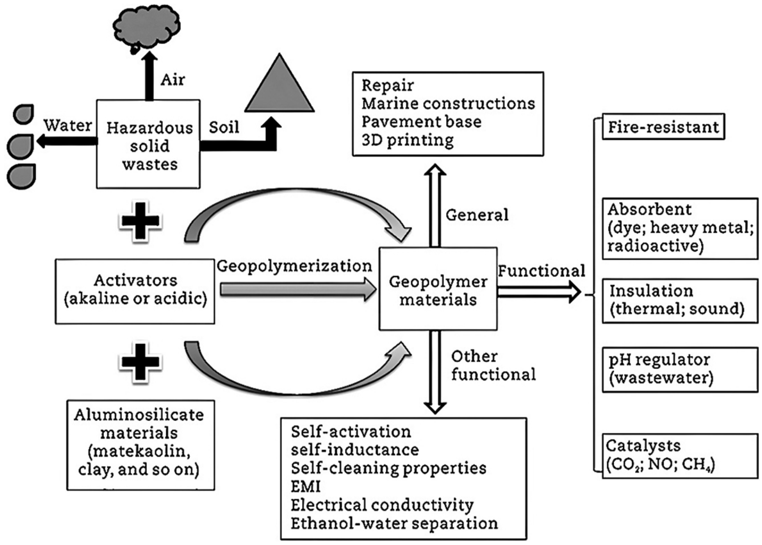

Figure 1. Self-assessment protocol for geopolymer and its process (Cong & Cheng, 2021)

Geopolymer concrete is an emerging trend in the production of concrete, offering a primary alternative to conventional binding materials like cement. It provides a sustainable solution for the environment by reducing the carbon footprint from the cement and offering better performance benefits. Geo-polymerization involves alumina- and silica-rich materials such as fly ash, slag, or metakaolin undergoing a chemical reaction in an alkaline environment, forming a binding material that densely packs the aggregates. Its enhanced binding properties surpass those of conventional methods, resulting in high-strength and durable geopolymer concrete. Additionally, the use of materials like fly ash and alternative slag reduces potential dumping issues, contributing to environmental sustainability by addressing waste disposal and promoting land conservation. In geopolymer concrete, alkali activators, which can be either liquid or solid, are used to activate the binding effect of aluminosilicate precursors such as fly ash, clay, or slag. Common activators include sodium hydroxide, sodium silicate, potassium hydroxide, and potassium silicate. In the one-stage method, all dry ingredients, including the precursor and any solid activators, are mixed first, and water are gradually added while stirring continuously to ensure homogeneous mixing and promote reactivity. This method is simpler and often preferred due to reduced handling risks associated with highly corrosive alkali solutions. In the two-stage method, the alkali activator solution is prepared 24 hours in advance to allow dissolution, after which it is mixed with the dry precursors and stirred for uniform consistency. The mixture is then transferred into molds, often with vibration for compaction, and may be covered with a polyethylene film to retain moisture during curing, depending on environmental conditions. The one-stage performer is generally encouraged for safety reasons, although further research may be required to determine the best practice for each specific mix. The geopolymer concrete production process is illustrated more clearly in Figure 2.

1.1. Strength parameters of geopolymer concrete

The evaluation of strength parameters is crucial in determining the appropriateness of geopolymer concrete as a sustainable substitute for conventional Portland cement concrete. The compressive strength, split tensile strength, and flexural strength are indicative of the performance of geopolymer concrete, aiding in the optimization of various mix proportions. The characteristics, properties, and effectiveness of precursors and activators across various curing conditions play a crucial role in determining strength development. Moreover, mathematical models can minimize reliance on extensive sampling and contribute to attaining optimal precision in mix design. The following sections provide comprehensive insights into the structural behavior, microstructural characteristics, and mathematical modelling approaches of geopolymer concrete.

1.1.1. Compressive strength

The following codes – IS 516: Part 1: Sec 1 (Bureau of Indian Standards, 2021), ASTM C39/C39M-21 (ASTM International, 2021), and BS EN 12390-3 (British Standards Institution, 2009a) were followed by the researchers to evaluate the compressive strength of geopolymer concrete. Furthermore, the use of fly ash as a precursor in geopolymer concrete mix design has effectively reduced the carbon footprint associated with cement production. Additionally, the reactivity between fly ash and alkali activators results in forming a denser matrix, which contributes to increased compressive strength (Davidovits et al., 2019). In M30-grade foam concrete, including fly ash as a precursor increased the compressive strength by 10–15% compared to conventional concrete under ambient curing conditions (Zhang et al., 2015). In another study, the maintenance of 60 °C curing temperatures accelerated the polymerization process, resulting in higher strength development (Hard-

Figure 2. Geopolymer concrete methodology

jito et al., 2005). 100% fly ash utilization in geopolymer concrete led to a 70% strength gain under 60 °C curing conditions (Poloju et al., 2023).

Including 40% GGBS (Ground Granulated Blast Furnace Slag) further enhanced strength, irrespective of the curing temperature, with an early strength gain of 25–30% (Nath & Sarker, 2014). When the GGBS content was increased to 50% in M50-grade concrete, early-age strength improvements reached 70–80% (Pan et al., 2018; Phul et al., 2019; Qu et al., 2022). This can be attributed to the fact that incorporating GGBFS accelerates the geopolymerization process, resulting in early strength gain. The formation of calcium-alumino-silicate gel (CASH) enhances the bonding ability within the matrix, contributing to improved strength (Nath & Sarker, 2014; Qu et al., 2022). A study in Algeria demonstrated that a 50:50 mixture of fly ash and GGBFS in M35-grade concrete resulted in a 57% strength improvement (N. K. Lee & H. K. Lee, 2013).

Moreover, palm oil fuel ash (an industrial by-product) was combined with 60% fly ash and 40% GGBFS to produce M40 concrete, which achieved a 50% increase in strength (Islam et al., 2014). This highlights the potential for other industrial by-products to be substituted for fly ash in regions where fly ash production is limited, promoting economical and sustainable concrete. Similarly, the use of metakaolin, another alumino-silicate material, resulted in a 63% improvement in strength (Pacheco-Torgal et al., 2008). Summary of the studies are presented in the Table 1.

1.1.2. Split tensile strength

IS 516: Part 1: Sec 1 (Bureau of Indian Standards, 2021), IS 5816 (Bureau of Indian Standards, 1999), and BS EN 12390-6 (British Standards Institution, 2009b) can be followed for evaluating the splitting tensile strength of geopolymer concrete. The results reported in the literature indicate that the splitting tensile strength of geopolymer concrete generally follows a trend similar to the increase observed in compressive strength. Specifically, studies have shown that curing geopolymer concrete made with 100% fly ash at 60 °C leads to a 15–30% enhancement in tensile strength compared to conventional cement-based concrete (Hardjito et al., 2005; Reddy et al., 2018; Shang et al., 2018). In ambient curing conditions, a 20–25% improvement in tensile strength was observed in geopolymer concrete when using a 70:30 ratio of fly ash to GGBFS (N. K. Lee & H. K. Lee, 2013; Qu et al., 2022). When this ratio was changed to 50:50, the tensile strength improved by 20–25% (Aydın, 2013; N. K. Lee & H. K. Lee, 2013).

Table 1. Summary of compressive strength

Materials used in geopolymer concrete	Fly Ash (%)	Remaining materials (%)	Conventional PCC grade	Strength achieved	Increase in strength (%) compared to PCC	References
Fly ash-based geopolymer foam concrete	70	–	M30	40 (28 days)	33%	Zhang et al. (2015)
Fly ash + GGBFS blend	60	GGBFS (40%)	M30	45 (28 days)	50%	Nath and Sarker (2014)
Slag-based geopolymer concrete	50	GGBS (50%)	M50	90 MPa (28 days)	80%	Qu et al. (2022)
Local materials (Algerian fly ash + slag)	50	GGBS (50%)	M55	55 MPa (28 days)	57%	Çelikten et al. (2019)
Fly ash + GGBFS	60	GGBFS (40%)	M50	80 MPa (7 days)	60%	Hardjito et al. (2005)
Fly ash-based geopolymer concrete	100	–	M40	Alkaline activator (100% sodium hydroxide + silicate)	70%	Poloju et al. (2023)
Fly ash + Metakaolin	70	Metakaolin (30%)	M35	63 MPa (28 days)	63	Pacheco-Torgal et al. (2008)
Fly ash + GGBS + Nylon crystal fibers	60%	GGBS (40%), Nylon fibers (~0.3–0.5%)	M40	54 MPa (28 days)	30%	Manoj Kumar et al. (2025)
Alkali activated slag + Dolomite + Fly ash	30%	GGBS (50–60%), Dolomite (20%)	–	Strength retained up to 400 °C	15%	Raj P K et al. (2025)
Fly ash + Stone dust (Geopolymer mortar)	60%	Stone dust (40%)	–	50 MPa (28 days)	20%	Yadav and Jha (2025)
Slag + Fly ash + Silica fume + Steel/Glass/ Basalt fibers (Fracture toughness study)	40%	Slag (50%), Silica fume (10%), Fibers (1%)	fracture test	Enhanced mode I/III fracture resistance		Karthik et al. (2024)

Geopolymer concrete made with low-calcium fly ash as a precursor showed an 18% enhancement in tensile strength, with early strength gains compared to conventional concrete (Nath & Sarker, 2017). For M50-grade geopolymer concrete, the incorporation of glass fibers led to a remarkable 30% improvement in tensile strength. The possible reason for the strength gain is the compatibility of the geopolymer matrix with steel and glass fibers, which has led to increased flexural strength, particularly in high-strength concrete (Shaikh, 2014). The literature is briefly summarized in Table 2.

1.1.3. Flexural strength

IS 516: Part 1: Sec 1 (Bureau of Indian Standards, 2021) and BS EN 12390-5 (British Standards Institution, 1999) are the standard codes generally followed for assessing the flexural strength of both conventional and geopolymer concretes. The flexural strength of geopolymer concrete has been reported to show a notable increase, following a trend similar to compressive strength improvements. In particular, studies on mixes prepared with 100% fly ash and cured at 60 °C have demonstrated a 15–28% enhancement in flexural strength compared to conventional cement-based concrete. Unlike conventional concrete, the polymerization process in geopolymer concrete is accelerated by curing at elevated temperatures (typically 60–100 °C), leading to faster strength development compared to the hydration process in conventional concrete (Hardjito et al., 2005; Olivia & Nikraz, 2012; Reddy et al., 2018). This improvement is attributed to the accelerated geopolymerization process under heat-curing conditions. Incorporating low-calcium fly ash as a precursor resulted in an 18% increase in flexural strength compared to conventional concrete, along with notable early strength gains (Nath & Sarker, 2017). Furthermore, for M50-grade geopolymer concrete, the inclusion of glass fibers led to a significant 30–35% improvement in flexural strength (Islam et al., 2014; Shaikh, 2014). Additionally, the use of industrial by-products such as palm oil fuel ash combined with fly ash showed a 20–22% increase in flexural strength (Chinnu et al., 2022). Other studies have shown that adding metakaolin to fly ash-based geopolymer concrete improved flexural strength by approximately 20–23%. The geopolymer matrix forms a very dense gel, which reduces porosity and increases densification (Pacheco-Torgal et al., 2008; Shah et al., 2020). When steel fibers were incorporated into M40 geopolymer concrete, a 30–40% increase in flexural strength was reported (Chen et al., 2021; Shaikh & Supit, 2014). This improvement is attributed to the reduced shrinkage and lower micro-cracking compared to traditional cement-based concrete, which enhances the structural integrity of the geopolymer concrete. The summary of the studies is depicted in Table 3.

Table 2. The summary of the split tensile strength studies

Material composition	Concrete grade	Achieved split tensile strength (MPa)	Increase compared to PCC (%)	Reference
100% Fly ash	M30	3.2	30	Kaur et al. (2018)
70% Fly ash, 30% GGBFS	M40	4.6	20–25	Khan et al. (2016)
100% Fly ash	M30	4.0	15	Olivia and Nikraz (2012)
Low calcium fly ash	M35	4.3	18	Nath and Sarker (2017)
Fly ash + Metakaolin	M40	4.7	20	Shah et al. (2020)
Rice husk ash + Fly ash	M35	3.9	14	Nuaklong et al. (2020)
Alkali-activated slag concrete	M50	6	20	Pan et al. (2018)
Metakaolin (40%) + Fly ash	M40	4.5	18	Pacheco-Torgal et al. (2008)
Fly ash + Glass fiberM35s	M50	6.02	30	Zuaiter et al. (2025)
50% GGBFS, 50% Fly ash	M50	6.5	20	Qu et al. (2022)
50% Fly ash + 50% GGBFS	M35	4.8	25	N. K. Lee and H. K. Lee (2013)
Palm oil fuel ash, bagasse ash	M35	4.4	22	Chinnu et al. (2022)
Fly ash + Nano-silica	M40	5.2	28	Zidi et al. (2021)
Palm oil fuel ash + 40% GGBFS, 60% Fly ash	M40	4.2	18	Islam et al. (2014)
Fly ash + 40% GGBFS	M30	3.5	20	Narayanan and Shanmugasundaram (2017)
Fly ash + Steel fibers	M50	6.8	40	Chen et al. (2021)
Fly ash	M40	5	10–15	Hardjito et al. (2005)

Table 3. The summary of the flexural strength studies

Material composition	Concrete grade	Achieved flexural strength (MPa)	Increase compared to PCC (%)	Reference
100% Fly ash	M30	3.5–3.7	15–28%	Kaur et al. (2018)
100% Fly ash	M30	3.5–4.0	15–28	Olivia and Nikraz (2012)
70% Fly ash, 30% GGBFS	M40	4.8–5.0	28–30	Khan et al. (2016)
Low calcium fly ash	M35	4.4–4.6	18–20	Sofi et al. (2007)
Fly ash + Metakaolin	M40	4.8–5.0	20–23	Shah et al. (2020)
Metakaolin (40%) + Fly ash	M40	4.7–4.9	20–23	Pacheco-Torgal et al. (2008)
Rice husk ash + Fly ash	M35	4.0–4.2	15–18	Endale et al. (2022)
Alkali-activated slag concrete	M50	5.3–5.5	25–30	Pan et al. (2018)
Palm oil fuel ash, bagasse ash	M35	4.3–4.5	20–22	Nuaklong et al. (2020)
Fly ash + Glass fibers	M50	6.4–6.5	30–35	Shaikh (2014)
50% GGBFS, 50% Fly ash	M50	6.1–6.2	30–35	Aydın (2013)
Palm oil fuel ash + 40% GGBFS, 60% Fly ash	M40	4.1–4.3	18–20	Abdulhaleem et al. (2024)
Fly ash + Steel fibers	M50	6.6–6.8	30–40	Shaikh and Supit (2014)
Fly ash + 40% GGBFS	M30	3.5–3.7	18–22	Nath and Sarker (2014)

1.1.4. Microstructural examination on the geopolymer concrete

Duxson et al. (2007) explored the microstructure of geopolymer concrete using Scanning Electron Microscopy (SEM). SEM images revealed a well-compacted matrix with fewer micro-cracks and lower porosity compared to conventional Ordinary Portland Cement (OPC) concrete. This denser matrix is a key factor contributing to the improved mechanical properties observed in geopolymer concrete. Using Mercury Intrusion Porosimetry (MIP), Al-Majidi et al. (2016) observed lower pore sizes in geopolymer concrete, further indicating a denser and more refined microstructure. In their study, Pacheco-Torgal et al. (2008) and Alexander and Shashikala (2022) employed X-ray Diffraction (XRD) to analyze the formation of calcium-alumino-silicate hydrate (CASH) gel. The inclusion of approximately 40% metakaolin with fly ash enhanced the overall bonding within the matrix due to the formation of amorphous phases, resulting in the development of CASH gel in the geopolymer matrix.

When combined with Ground Granulated Blast Furnace Slag (GGBFS), the microstructure of geopolymer concrete became more homogeneous and dense, contributing to enhanced strength and durability. This was analyzed through Energy-Dispersive X-ray Spectroscopy (EDS) and SEM (Nath & Sarker, 2014; Nath et al., 2016). Singh et al. (2015) observed a strong chemical bond between fly ash and slag through EDS analysis, further reinforcing the matrix. The addition of nano-silica (N) to the fly ash (FA) and GGBFS (G) in a ratio of 10:55:35 filled the gaps within the matrix, resulting in increased densification and thermal stability. Similarly, comparable densification was observed when rice husk ash was incorporated in place of nano-silica (Alharthai et al., 2025).

Furthermore, incorporating steel fibers into FA and GGBFS in a 50:50 ratio led to a 30–40% increase in flexural strength (Chen et al., 2021; Shaikh & Supit, 2014). The addition of fibers decreased microcracking and built a more resilient structure. Additionally, a mix of fly ash, GGBFS, and polypropylene fibers in the ratio of 60:30:10 resulted in decreased crack propagation and increased structural integrity. These microstructural enhancements, observed through various analytical techniques, comprehensively understand the superiority and durability of geopolymer concrete compared to traditional cement-based concrete.

Thapa et al. (2024) review various alternative SCMs that can be used in geopolymer concrete, including slag, metakaolin, rice husk ash, and silica fume. These materials offer similar chemical compositions to fly ash and can potentially provide comparable or even enhanced performance in geopolymer concrete mixes.

2. Need for sustainable alternatives to conventional precursors in geopolymer concrete

Activators and precursors are two critical elements necessary for the geopolymerization process. Traditional activators, usually comprising sodium and potassium compounds, require substantial energy for their synthesis. This imposes considerable environmental strain owing to the utilization of quartz sand and sodium carbonate (Bernal et al., 2015; Konduru et al., 2025). The synthesis of sodium silicate necessitates exceedingly high temperatures and significant fossil fuel use, leading to considerable CO_2 emissions. The extraction of silica and alkalis leads to the depletion of natural resources (Rajan & Kathirvel, 2021; Vinai & Soutsos, 2019). The sustainability challenges have prompted an investigation into agro-industrial wastes abundant in silica, such as rice husk ash (RHA), sugarcane bagasse ash, and waste glass, as potential alternative sources for the synthesis of activators. Research has shown that sodium silicate obtained from RHA exhibits performance similar to that of commercial activators in geopolymers based on metakaolin and fly ash (Kathirvel & Nassar, 2025; Tchakouté et al., 2016a, 2016b; Tong et al., 2018). Binders derived from sugarcane bagasse ash exhibit notable mechanical strength and thermal stability (Tchakouté et al., 2017). Additionally, the inclusion of waste glass has enhanced the rheological characteristics and long-term durability of alkali-activated materials (Puertas & Torres-Carrasco, 2014; Torres-Carrasco et al., 2015; Vinai & Soutsos, 2019).

The streamlined management, practical field use, decreased water usage, and diminished CO_2 emissions resulting from the comprehensive utilization of agricultural ashes highlight their promise as sustainable options (Murali et al., 2024; Nassar et al., 2024). Overall, the utilization of industrial and agricultural wastes for synthesizing activators has shown mechanical properties that are comparable to or superior to those of traditional sodium silicate (Bernal et al., 2015; Kathirvel et al., 2020). Additionally, these materials provide environmental advantages, including a lower CO_2 footprint and the resolution of waste disposal challenges (Rajan & Kathirvel, 2021), economic efficiency (Tchakouté et al., 2016a), and compatibility with circular economy principles (Nassar et al., 2024).

Traditional precursors like fly ash, GGBFS, metakaolin, and silica fume are widely used in geopolymer concrete due to their pozzolanic activity. Their role in forming calcium-silicate-hydrate (CSH) gel leads to a denser matrix, enhancing mechanical properties. However, rice straw ash (RSA) stands out as a compelling alternative, offering distinct advantages over conventional materials. Unlike fly ash, a by-product of thermal power plants from coal combustion, whose availability is diminishing due to the decreasing use of coal, RSA is a by-product of agricultural residues and is widely accessible without the need for extensive processing. While metakaolin is highly reactive and effective in improving strength and durability, it is costly and energy-intensive to produce, raising both economic and ecological concerns. In contrast, RSA is sustainable, renewable, and abundantly available in rice-producing regions, making it more economical. GGBFS, although effective, is geographically restricted to steel-producing areas and also involves energy-intensive processing. Silica fume, though it further refines the microstructure of concrete, is expensive and not as accessible. RSA, being a locally available agricultural waste, is cost-effective and aids in waste management, aligning with sustainable construction practices. Its wider availability in agricultural regions makes it a viable and environmentally friendly alternative for geopolymer concrete production. The following summary Table 4 has led to explore need for the agri-waste by-products

2.1. Rice straw and husk process

Rice ranks among the most extensively cultivated cereal crops worldwide, with an estimated annual yield of 750 million tons. Approximately 20–22% of the paddy weight consists of rice husk, while rice straw accounts for almost 1.5 times the weight of the grain. For each ton of rice produced, around 200 kg of husk and 1.5 tons of straw are generated. In countries such as India and China, this results in tens of millions of tons of rice-based agricultural waste each year, most of which is either underutilized or burned in open fields, significantly exacerbating air pollution and greenhouse gas emissions.

Table 4. Summary of the precursors in geopolymer concrete

Alternative precursor	Disadvantage	Primary limitations
Fly Ash	Decreasing availability, variability in quality, unburnt carbon affects performance	Dependency on coal power plants, quality inconsistency, environmental concerns
GGBFS	Limited availability, high cost, variability in quality, high calcium content	Regional dependence, environmental impact from production
Metakaolin	High cost, energy-intensive production, limited availability, handling and safety concerns	Economic constraints, environmental concerns due to energy consumption
Palm oil fuel ash (POFA)	High variability, limited regional use, potential impurities, handling challenges	Geographical dependence, quality control issues
Silica fume	High cost, limited availability, handling issues, workability concerns	Economic barriers, health and safety risks
Volcanic ash and other natural pozzolans	Scarcity, variable composition, transportation costs, processing requirements	Geographical constraints, economic feasibility

Rice straw is abundantly available globally, with large quantities generated annually as agricultural waste (Agwa et al., 2020; United Nations, 2013). In India alone, production ranged between 104 and 122 million tons annually from 2015 to 2021, yielding a significant amount of rice husk ash (5–6 million tons per year), which contains approximately 95% silica (Nassar et al., 2024). Rice straw and rice husk is primarily separated during the milling process composed of cellulose, hemicellulose, and lignin, along with smaller amounts of silica, ash, and other organic compounds (Ahsan & Hossain, 2018; Amin et al., 2023; Pandey & Kumar, 2019b). Traditionally, rice straw has been used for purposes such as animal bedding, mulching, and fuel in rural areas (Butt et al., 2025; Elfadaly et al., 2025).

Historically, rice husk has been considered a waste product and often disposed of by burning or landfilling, leading to environmental concerns (Kopuru et al., 2025). However, advancements in technology and research have led to the exploration of innovative uses for rice straw and rice husk, including their conversion into biofuels, bio-composites, paper products, and building materials (Alyami et al., 2023; Hakeem et al., 2023; Khankhaje et al., 2025; Suomie et al., 2025). The statistics of the agri-residue are presented in Figure 3.

2.2. Detail operation of workability, setting time of geopolymer concrete

The influence of rice by-products, such as rice straw and rice husk, on the fresh properties of geopolymer concrete is an important consideration. Adding these by-products can affect workability, which refers to the ease of mixing, placing, and compacting concrete. Rice straw and rice husk may act as fillers or additives in geopolymer mixes, altering the rheological properties of the fresh concrete (Amin et al., 2023; Narattha et al., 2024). The inclusion of rice husk ash (RHA) reduces the slump value of geopolymer concrete, indicating a decrease in workability. In contrast, rice straw ash (RSA) influences the viscosity and flow behavior of the mix (Liu et al., 2020; Nuaklong et al., 2020). This is due to the fine particle size and rich silica content of RSA, which enhance packing density and interparticle friction within the matrix (Chelluri & Hossiney, 2024). Additionally, the presence of cellulose and lignin in RSA acts as natural fibers, potentially improving cohesiveness and reducing segregation during the placement of the concrete mix (Pandey & Kumar, 2019a). However, optimizing the proportion of RSA is crucial, as excessive amounts may lead to challenges in mixing and compaction (Si et al., 2025).

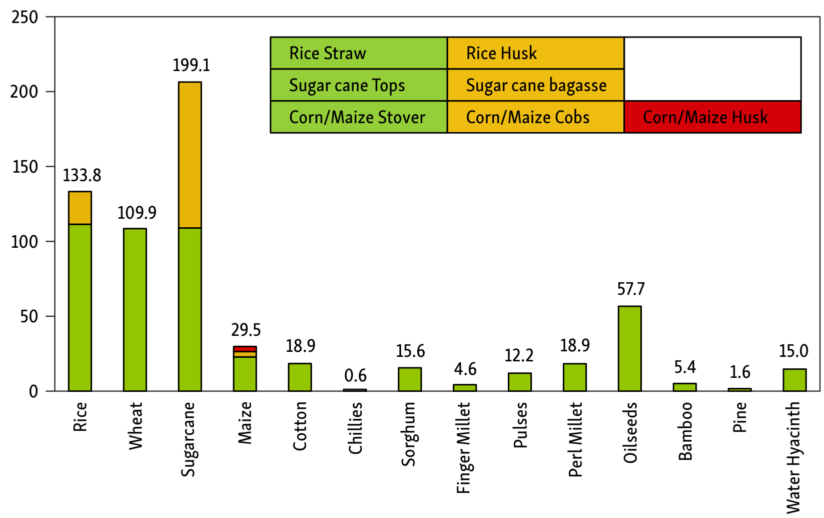

Figure 3. Agri-residue in India (Mayhoub et al., 2021; Singh et al., 2016)

2.3. Impact on setting time and early-age strength development in geopolymer concrete using rice by-products

The chemical composition and reactivity of the mix can affect the rate of hydration and setting, leading to variations in setting time. Additionally, the incorporation RHA and RSA may influence the microstructure and pore distribution of geopolymer concrete, thereby affecting early-age strength development and the overall mechanical properties of the hardened concrete. Understanding the effects of rice by-products on workability, setting time, and early-age strength development is essential for optimizing the performance of geopolymer concrete mixes containing these sustainable alternatives. Proper material characterization, mix design optimization, and quality control measures are necessary to ensure the successful utilization of rice by-products in geopolymer concrete production.

Research has examined the fresh and hardened properties of alkali-activated slag (AAS) with and without RSA, utilizing experimental methods to analyze reaction kinetics and microstructure. Findings from Hakeem et al. (2022) show that RSA acts as a precursor and internal curing agent in AAS, aiding the formation of CSH-hydrate gel and reducing both autogenous and drying shrinkage. RSA's porous nature improves internal curing by absorbing and releasing liquid, thereby enhancing the paste's consistency index.

Further examinations were conducted using sugarcane straw combined with 20–30% clay, heated at 800 °C and 1000 °C, along with lime, to specifically analyze the reaction kinetics. The accelerated chemical method was used to measure the progress of lime reactivity. The kinetic-diffusive model (KDM) was applied and fitted to determine kinetic coefficients, including the reaction rate constant (Athira & Bahurudeen, 2022). The pozzolanic activity index was thoroughly characterized based on these values. When compared with an indirect method (conductometry), the results confirmed the validity of the KDM for assessing pozzolanic reactions, regardless of the method used for evaluating pozzolanic activity.

Experimental research on composite boards designed for construction, using rice husk waste, has also been conducted. These boards are prepared by blending recycled rubber granules in the proportions of 50:50 and 75:25 by weight. These boards are created by blending rice husk with expanded cork or recycled rubber granules in 50/50 and 75/25 weight percent ratios. A polyurethane pre-polymer based on TDI, constituting 20% of the fillers' mass, serves as the binder and several small scale experiments were caried out to assess various properties (Narayanan & Shanmugasundaram, 2017).

In terms of innovative construction materials, straw ash concrete, which utilizes agricultural by-products in place of cement, has been studied for its mechanical and durability properties. Research by Prabhakar et al. (2024) focused on split tensile strength, compressive strength, bond strength, and corrosion behavior of reinforced straw ash concrete, considering factors such as straw ash dosage, rebar diameter, and concrete strength grades. The analysis consisted of concrete specimens (144), pull-out specimens (108), and corroded specimens (30) indicating that higher straw ash dosages lower rebar bond strength, especially with smaller rebar diameters. Corrosion tests suggest better corrosion resistance in straw ash concrete compared to ordinary concrete, demonstrating its potential as a mineral admixture at a 10% replacement ratio for concrete grades M20 and M30.

Further studies have explored the use of rice straw ash (RSA) and micro-silica (MS) as pozzolans in rigid pavements. Mortar cubes were cast with different combinations of RSA and MS, and both mechanical and micro-level analyses were conducted. The results indicated that RSA and MS improved various concrete strengths, ranging from 7% to 24%, respectively, as validated through XRD and SEM analyses. Cost comparisons revealed that incorporating 10% RSA reduced slab thickness by 11%, concrete costs by 3%, and construction costs for a 4-lane National Highway (NH) by 14% (Pandey & Kumar, 2020).

The contemporary trend in construction leans towards incorporating high-performance and sustainable materials that are highly reactive to enhance strength, durability, and sustainability. A sustainable mortar cube with varying proportions of micro-silica, ranging from 5% to 25% as a replacement for cement, was tested for both fresh and hardened properties, and the results were compared to a control mortar. The findings indicate that reactive silica acquired from RHA holds promise as a valuable resource in the development of high-performance and sustainable cement mortar (Nana et al., 2021). Furthermore, RHA was directly used to replace conventional cement in proportions ranging from 0% to 15%, with 2% increments, to study its durability and strength in comparison to conventional concrete. These studies revealed that RHA replacement led to a decrease in strength and at higher RHA contents, water absorption increased due to greater porosity.

RSA and cotton stalk ash (CSA) were also used in place of cement for the preparation of self-compacting concrete and compared with the control mix. A total of seven mixes were prepared, with replacement ratios of 5%, 10%, and 15% separately using RSA and CSA, including a control mix. Pumice was used as lightweight aggregate at a replacement level of up to 80%. The results indicated reduced workability with increased RSA and CSA ratios but improved hardened properties, except at the 20% replacement ratio. SEM analysis revealed that 10% RSA resulted in more densely packed concrete than the control mix (Narattha et al., 2024).

The wheat straw ash (WSA) samples were prepared with a water-to-cement ratio of 0.6 and subjected to autoclaving for 2.5 hours under 2 MPa pressure. Three replacement levels of 3.6%, 7.3%, and 10.9% WSA by weight of sand were examined by preparing mortar specimens. The optimal replacement level was found to be 10.9%, showing an improvement of 87% in compressive strength, 67% in tensile strength, and 71% in flexural strength. SEM analysis revealed a closely compacted structure at the 7.3% replacement level (Si et al., 2025). Additionally, in the regions of Khyber Pakhtunkhwa, RH-based concretes were explored by exposing them to high temperatures, and their mechanical behavior was examined. These RHA-based mixtures showed a linear increase in consistency and setting time, a decline in alkali-silica reaction, and improved compressive and flexural strength. Single RHA replacement showed promising strength results at 90 days of curing.

3. Mathematical modelling

There is a wide range of powerful tools available for establishing mathematical relationships aimed at optimizing the performance of rice by-product-based geopolymer concrete. Some of the key tools include Hybrid Artificial Neural Networks (ANN), Scheffe's Polynomial Model, Osadebe's Degree Polynomial Model, Extreme Gradient Boosting (XGBoost), Gradient Boosting Machine (GBM), and Convolutional Neural Networks (CNN). These models are particularly useful in predicting the mechanical properties (like compressive strength, tensile strength, and workability) based on input variables such as composition, curing conditions, water-to-cement ratio (w/c), and the variability of rice by-products (e.g., rice husk ash or rice straw).

Iqtidar et al. (2021) developed a HANN model, optimization carried out by a reptile search algorithm to account the compressive strength of the RHA concrete. This model was developed based on the 6 inputs such as RHA, cement content, water to cement ratio, curing time and aggregates, which resulted in high prediction rate of correlation factor (R^2) 0.97. This method has produced a frame work to analyse the RHA concrete mechanical properties. These mathematical models provide significant advantages, as they can determine the optimal mix design with variations in moisture content, particle size, and other material properties, without resorting to the laborious and time-consuming conventional trial-and-error approach. As such, they offer increased efficiency, optimization, scalability, and customization in concrete mix design. However, one limitation is the requirement for a large experimental dataset to feed into these models. The accuracy and precision of the predictions rely heavily on the quality and volume of the experimental data collected (Isleem et al., 2023, 2024, 2025). Rather than relying on meticulous laboratory techniques for mix optimisation, AI models such as Gene Expression Programming (GEP), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Artificial Neural Networks (ANN) have been implemented to forecast strength parameters. The compressive and flexural strength of geopolymers produced from sugarcane bagasse and banana peel ash have been accurately estimated by these models. Alaneme et al. (2024a) compared a variety of AI tools for optimising the mix design in a critical review, emphasising their potential to decrease both cost and experimental effort. ANFIS demonstrated the maximum prediction accuracy for mechanical properties among these methods. Additionally, a simplified methodological framework was proposed to align the design process with practical applications by incorporating oxide molar ratios and performance-based criteria (Alaneme et al., 2024b). In their study, Alaneme et al. (2023) underscored the environmental advantages of employing agro-waste-based materials in a systematic and environmentally favourable manner from a sustainability perspective. The prediction process is substantially simplified by mathematical models; however, they must be trained on a unique combination of features to guarantee reliable and accurate results. This process still necessitates detailed and comprehensive experimental data.

4. Challenges and limitations observed in using rice straw and rice husk

4.1. Variability in properties

Rice straw and rice husk exhibit variability in their physical and chemical properties, such as particle size, shape, moisture content, and composition. This variability can present challenges in achieving consistent performance in geopolymer concrete mixes (Al-Khalaf & Yousif, 1984; Chelluri & Hossiney, 2024). Factors like rice variety, harvesting methods, processing techniques, and storage conditions can further influence their properties, impacting their performance when incorporated into geopolymer concrete.

4.2. Particle size and shape

Rice straw and rice husk particles vary in size, ranging from fine dust-like particles to larger fibrous strands (Endale et al., 2022). Their irregular shapes and heterogeneous nature can affect packing density, interlocking behavior, and particle distribution within the concrete mix. These variations can influence the workability, rheology, and mechanical properties of geopolymer concrete, potentially leading to issues such as segregation, bleeding, or poor compaction (Khan et al., 2012).

4.3. Moisture content

The moisture content of rice straw and rice husk can differ due to factors such as climate, storage conditions, and processing methods (Amran et al., 2021). High moisture content may increase the water demand in concrete mixes, affecting the water-to-binder ratio and workability. Conversely, low moisture content can cause these by-products to absorb water from the mix, potentially altering setting time, hydration kinetics, and strength development (Al-Khalaf & Yousif, 1984).

4.4. Composition

The chemical composition of rice straw and rice husk is influenced by factors like rice variety, soil conditions, and agricultural practices (Narattha et al., 2024). For example, rice husk predominantly consists of silica, along with organic matter, cellulose, hemicellulose, and lignin, while rice straw contains similar organic constituents but also has silica, potassium, phosphorus, and other minerals (Chelluri & Hossiney, 2024). These variations in composition can influence reactivity, pozzolanic activity, and contribution to the geopolymerization process in concrete mixes (Nuaklong et al., 2020).

4.5. Surface characteristics

Surface properties such as roughness, porosity, and chemical reactivity of rice straw and rice husk can vary depending on processing methods and environmental exposure (Khan et al., 2012). These surface characteristics affect the adhesion, bonding, and interaction between the rice by-products and the geopolymer binder in the concrete mix. Such variability in surface properties may influence the mechanical interlock, durability, and long-term performance of rice-based geopolymer concrete (Narayanan & Shanmugasundaram, 2017).

4.6. Workability issues

Incorporating rice straw and rice husk into geopolymer concrete mixes can lead to workability challenges such as reduced flowability, increased viscosity, and segregation (Amran et al., 2021). These issues can hinder handling and placement of the fresh concrete. Addressing such workability concerns requires careful consideration of mix design parameters, including particle size distribution, water-to-binder ratio, and the use of superplasticizers and admixtures (Narattha et al., 2024). Proper processing, screening, and pre-treatment of rice straw and rice husk can also help mitigate these challenges, optimizing the workability of geopolymer concrete (Al-Khalaf & Yousif, 1984). On-site monitoring and quality control are essential to ensure the successful placement and performance of rice-based geopolymer concrete in construction applications.

4.7. Durability concerns

The long-term durability of geopolymer concrete containing rice by-products is another challenge, as these materials can impact resistance to factors such as shrinkage, cracking, chemical attack, and frost damage (Chelluri & Hossiney, 2024). Addressing these durability concerns requires detailed material characterization and optimization of the mix design. Supplementary additives, enhanced pore structure, and protective surface treatments can help mitigate issues related to shrinkage, cracking, and chemical resistance, improving the durability of rice-based geopolymer concrete (Nath & Sarker, 2014).

4.8. Material characterization

Further research is needed to systematically characterize the physical, chemical, and mechanical properties of rice straw and rice husk, including their variations and effects on geopolymer concrete performance (Amran et al., 2021; Khan et al., 2012). By gaining a deeper understanding of the behavior of these by-products, researchers can improve material selection, mix design optimization, and quality control, enhancing the sustainability of rice by-products in geopolymer concrete production. This research will also contribute to the development of standards, guidelines, and best practices for incorporating rice by-products into construction materials, thereby advancing sustainable construction and waste utilization (de Sensale, 2006).

5. Solutions to face challenges and to overcome the limitations

The variability in the physical and chemical properties of rice straw and rice husk can be addressed through thorough material characterization, including analyses of composition, particle size, and reactivity. This helps achieve consistent quality control (Khan et al., 2012). Standardized processing techniques such as controlled burning can ensure a consistent ash content and reduce contaminants, minimizing variability in the resulting material (Prabhakar et al., 2024). Pre-processing methods, such as sieving or milling, help in achieving uniform particle size, thereby reducing the impact of variability in geopolymer concrete (Chelluri & Hossiney, 2024).

The use of superplasticizers and admixtures can improve the rheological properties of the mix to manage irregular particle sizes. Adjusting the water-to-cement ratio and incorporating materials like silica fume or nano-silica enhances compaction and packing density, even with non-uniform particles, improving interlocking in the concrete matrix (Hakeem et al., 2023; Narayanan & Shanmugasundaram, 2017). Alkali activation of the interface between ash and binder further enhances bonding, leading to a more resilient and durable structure (Khan et al., 2012).

To address moisture content variability, pre-drying or partial calcination of rice husk and straw before mixing can reduce excess moisture (Hakeem et al., 2022). Additionally, techniques such as superabsorbent polymers or adjusting the amount of rice straw ash (RSA) in the mix can help control moisture retention during curing (Al-Khalaf & Yousif, 1984). Pre-soaking can also improve structural integrity and reduce segregation in the mix.

Blending rice by-products with supplementary cementitious materials (SCMs) such as GGBFS or fly ash ensures more consistent mechanical properties and strength development (El-Sayed, 2021; Rani & Jaya Krishna, 2022). Viscosity-modifying agents (VMAs), along with appropriate adjustments to the water-to-cement ratio can also improve workability (Narattha et al., 2024).

To enhance the durability of geopolymer concrete, nano-materials like nano-silica and nano-clay can be introduced, which help in creating a non-porous structure. The addition of steel fibers can further resist crack formation and offer protection against aggressive chemical attacks

(Pandey & Kumar, 2019b). Ongoing research and the application of advanced microstructural analysis techniques, such as XRD, SEM, and TGA, can help reduce variability and ensure the production of high-quality concrete made from rice by-products (Amin et al., 2023).

6. Conclusions

The transition from traditional cement to sustainable binders is essential due to the environmental impact associated with raw material extraction and carbon emissions in cement manufacturing. Geopolymers, originating from industrial and agricultural by-products like fly ash and rice straw ash, represent a viable alternative due to their enhanced mechanical properties and durability. The sustainability of geopolymers is influenced by the activators employed in their synthesis. Conventional activators, including sodium silicate and potassium-based compounds, require significant energy input and depend largely on non-renewable resources, resulting in increased CO_2 emissions and resource depletion. This has guided research to focus on the use of agro-industrial wastes high in silica, such as rice husk ash, sugarcane bagasse ash, and waste glass, as alternative precursors for the production of activators. Research indicates that these materials not only diminish environmental impact but also sustain or improve the performance of geopolymeric binders. Integrating agricultural residues for the development of both precursors and activators constitutes a comprehensive strategy for fostering a sustainable, resource-efficient, and circular construction industry in the future.

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