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GEOPOLYMER DEVELOPMENT FROM INDONESIAN LOCAL MATERIALS: A REVIEW

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A B S T R A C T

Geopolymers have emerged as promising low-carbon binders capable of utilizing industrial and agricultural by-products as alternatives to ordinary Portland cement. Indonesia presents a strategic context for geopolymer development due to the abundance of coal fly ash from coal-fired power plants and silica-rich agricultural residues such as rice husk ash. This paper provides a comprehensive review of geopolymer development using Indonesian local materials by synthesizing findings from thirty peer-reviewed national and international studies published between 2019 and 2025. The review focuses on precursor characteristics, mix design strategies, alkali activator systems, curing regimes, and reported mechanical, durability, and microstructural performance. Indonesian fly ash is identified as the dominant and most viable geopolymer precursor, although significant variability in chemical composition and reactivity is reported across different sources. Supplementary materials such as rice husk ash and other agricultural by-products can enhance sustainability and silica availability when used in controlled proportions. Curing regime plays a decisive role, with elevated temperature curing accelerating early-age strength development, while ambient curing—more representative of practical construction conditions in Indonesia—results in slower but progressive geo-polymerization. Despite substantial research progress, key challenges remain, including precursor variability, limited long-term durability data under tropical conditions, and the lack of standardized mix design guidelines. This review consolidates dispersed research outcomes into a coherent framework, identifies critical research gaps, and provides direction for advancing geopolymer technology toward reliable and sustainable construction and environmental applications in Indonesia.

Keyword

Geopolymer;
Indonesian local materials;
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rice husk ash;
alkali activation;
curing regime;
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Page 46-61

1. INTRODUCTION

Geopolymers are inorganic aluminosilicate binders formed through alkali activation of silica- and alumina-rich materials, offering a promising alternative to ordinary Portland cement (OPC) in the context of sustainable construction. Unlike OPC hydration, geo-polymerization involves the dissolution of aluminosilicate precursors in highly alkaline environments, followed by polycondensation reactions that form a three-dimensional amorphous to semi-crystalline network. This mechanism enables the utilization of various industrial and agricultural by-products as precursor materials while significantly reducing greenhouse gas emissions associated with cement production (Hidayati et al., 2020; Sutra et al., 2021). Indonesia presents a particularly strategic context for geopolymer development. The country operates numerous coal-fired power plants that generate large volumes of coal fly ash, much of which remains underutilized or disposed of as waste. Several studies have demonstrated that fly ash sourced from Indonesian power plants contains sufficient reactive silica and alumina to function as a viable geopolymer precursor, although its chemical composition, amorphous content, and calcium level vary considerably between sources (Hidayati et al., 2020; Salain et al., 2021; Hartono, 2022). This variability directly influences geopolymerization kinetics, strength development, and long-term performance, making Indonesia an important case study for material-specific geopolymer research.

In parallel with industrial by-products, Indonesia also generates substantial quantities of agricultural residues, particularly rice husk ash (RHA), due to its status as a major rice-producing country. Properly processed RHA is characterized by high silica content and has been investigated as a supplementary geopolymer precursor. Experimental studies conducted in Indonesia report that partial substitution of fly ash with RHA can enhance silica availability and contribute to geopolymer matrix formation when used in controlled proportions, whereas excessive substitution leads to strength reduction due to insufficient alumina content (Ilyas et al., 2022; Olii et al., 2025; Insyira et al., 2023). Similar observations have been reported in international studies involving blended fly ash–agricultural ash systems (Nurtanto et al., 2020). Over the past decade, research on geopolymers derived from Indonesian local materials has expanded significantly, particularly in national journals indexed in the Indonesian Science and Technology Index (Sinta), alongside a growing number of Scopus-indexed international publications. These studies span a wide range of topics, including precursor characterization, mix design optimization, alkali activator systems, curing regimes, and performance evaluation in terms of mechanical strength, durability, and microstructural development (Salain et al., 2021; Hartono, 2022; Hidayati et al., 2020). In addition, Indonesian fly ash–based geopolymers have been explored for non-structural and environmental applications, such as soil stabilization and heavy metal immobilization, demonstrating multifunctional potential beyond conventional concrete systems (Sutra et al., 2021; Fansuri et al., 2024).

Despite the growing body of experimental work, existing geopolymer review articles generally adopt a global perspective and rarely provide a focused synthesis of studies specifically addressing Indonesian local materials. As a result, critical issues such as inter-

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Page 46-61

source variability of Indonesian fly ash, the role of silica-rich but alumina-poor agricultural ashes, and the practicality of curing regimes under tropical conditions are often discussed in a fragmented manner. Moreover, many experimental studies evaluate individual parameters—such as mix composition or curing temperature—in isolation, limiting cross-comparison and broader interpretation (Hidayati et al., 2020; Rangan et al., 2023). Accordingly, this paper presents a comprehensive review of geopolymer development using Indonesian local materials by synthesizing findings from thirty peer-reviewed national and international studies. The review focuses on precursor characteristics, mix design and alkali activator systems, curing regimes, and reported mechanical, durability, and microstructural performance. By consolidating dispersed research outcomes into a coherent framework, this review aims to clarify current research trends, identify key challenges and knowledge gaps, and support the advancement of geopolymer technology for sustainable construction and environmental applications in Indonesia.

2. SCOPE AND METHODOLOGY OF THE REVIEW

2.1 Scope of the Review

This review is designed to synthesize and critically evaluate geopolymer research conducted using Indonesian local materials, with a deliberate focus on experimental studies that report material characterization, mix design, curing regimes, and performance outcomes. The scope is intentionally bounded to avoid generic discussion of geopolymer technology and to ensure that the synthesis reflects conditions, constraints, and opportunities relevant to the Indonesian context. The primary emphasis of this review is placed on fly ash sourced from Indonesian coal-fired power plants, which dominates geopolymer research in Indonesia. Studies investigating supplementary or alternative precursors-such as rice husk ash, rice straw ash, lateritic soil, ground granulated blast furnace slag, and other locally available aluminosilicate materials-are included when these materials are explicitly combined with or evaluated as part of geopolymer systems relevant to Indonesia. Both structural applications (e.g., geopolymer mortar and concrete) and non-structural or environmental applications (e.g., soil stabilization and heavy metal immobilization) are considered.

The review covers geopolymer systems in the form of paste, mortar, and concrete. Studies focusing solely on ordinary Portland cement, blended cement systems without geopolymer network formation, or purely numerical simulations without experimental validation are excluded. This selection ensures that the review remains centred on material development and performance rather than theoretical modelling alone. The literature corpus reviewed in this paper consists of thirty peer-reviewed journal articles published between approximately 2019 and 2025. These articles comprise a balanced combination of: 1) International publications indexed in Scopus, including journal articles and selected conference papers that provide substantial experimental data, and 2) National publications indexed in the Indonesian Science and Technology Index (Sinta), which offer detailed insight into local materials, experimental practices, and application-oriented research.

2.2 Review Methodology

This review adopts a structured narrative review methodology. Rather than performing a quantitative meta-analysis, a qualitative synthesis approach is employed due to the significant heterogeneity observed across the reviewed studies. Variations in fly ash source, precursor blending strategy, alkali activator composition, curing regime, specimen geometry, and testing standards make direct statistical aggregation impractical and potentially misleading. The review process involves three main stages. First, the selected articles are systematically screened and categorized according to their primary research focus, including: 1) precursor material characteristics, 2) mix design and alkali activator systems, 3) curing regimes, and 4) mechanical, durability, and microstructural performance. Second, comparative analysis is conducted within each thematic category to identify consistent trends, contradictions, and source-dependent behaviours reported across studies. Particular attention is given to interactions between material characteristics, curing regime, and performance, as these interactions are repeatedly highlighted as critical in Indonesian geopolymer research. Third, cross-cutting synthesis is performed to identify overarching challenges and research gaps, such as material variability, limited long-term durability data under tropical conditions, and the lack of integrated experimental frameworks. These insights form the basis for the discussion of future research directions presented in Section 7.

2.3 Structure of the Review

Based on the defined scope and methodology, the remainder of this paper is organized as follows. Section 3 reviews Indonesian local materials used as geopolymer precursors, with emphasis on fly ash and supplementary materials. Section 4 discusses mix design strategies and alkali activator systems reported in the literature. Section 5 examines curing regimes and their influence on geo-polymerization and performance. Section 6 synthesizes reported mechanical, durability, and microstructural performance outcomes. Finally, Section 7 highlights key challenges, research gaps, and future perspectives for geopolymer development using Indonesian local materials.

3. REVIEW LITERATURE

3.1 Indonesian Local Materials as Geopolymer Precursors

Fly ash is the most extensively investigated geopolymer precursor in Indonesia and constitutes the backbone of the reviewed literature. This predominance is associated with the widespread operation of coal-fired power plants and the continuous generation of fly ash across multiple regions. Experimental studies consistently report that Indonesian fly ash contains sufficient reactive silica (SiO_2) and alumina (Al_2O_3) to enable alkali activation, although its geopolymer reactivity varies substantially depending on source-specific characteristics (Hidayati et al., 2020; Salain et al., 2021; Hartono, 2022). A recurring finding across both national and international studies is the heterogeneity of Indonesian fly ash. Comparative investigations involving fly ash from multiple power plants reveal pronounced differences in oxide composition, amorphous phase content, particle fineness, and calcium oxide concentration, all of which directly influence dissolution kinetics and strength development (Hidayati et al., 2020; Bastian, 2025). National studies further demonstrate that fly ash with moderate CaO content may exhibit mixed reaction mechanisms, producing both geopolymer gel and calcium-rich hydration products, thereby increasing sensitivity to curing regime and moisture control (Hartono, 2022; Salain et al., 2021). These findings indicate that Indonesian fly ash cannot be treated as a uniform geopolymer raw material. Instead, source-specific characterization should be considered a prerequisite for mix design and curing optimization, particularly when ambient curing is targeted for practical applications.

Rice husk ash (RHA) is the most frequently studied agricultural by-product in Indonesian geopolymer research, reflecting the country's large-scale rice production. Properly processed RHA is characterized by high silica content, often in amorphous form, which enables its use as a supplementary geopolymer precursor. Several Indonesian studies report that partial substitution of fly ash with RHA enhances silica availability and contributes positively to geopolymer matrix formation when replacement levels are carefully controlled (Ilyas et al., 2022; Olii et al., 2025; Insyira et al., 2023). However, the literature consistently emphasizes that RHA alone is insufficient as a sole geopolymer precursor due to its low alumina content.

Excessive replacement of fly ash with RHA leads to a reduction in compressive strength, reflecting an imbalance in the Si/Al ratio required for stable geopolymer network formation (Salain et al., 2021; Nurtanto et al., 2020). Similar trends are reported in international studies involving rice straw ash and other silica-rich agricultural residues, which highlight the necessity of combining such materials with alumina-bearing precursors (Rangan et al., 2023). Beyond RHA, limited studies have explored other agricultural ashes, such as rice straw ash, as supplementary materials. While these materials offer high silica content, their practical application remains constrained by processing requirements and variability in ash quality. Astuti et al. (2025) investigated rice husk ash–based geopolymer mortar as a patch repair material for deteriorated concrete, emphasizing the role of alkali activator composition on mechanical performance. Using NaOH–Na_2SiO_3 activators with varying proportions, the study identified an optimal activator content that maximized compressive strength while maintaining adequate workability. Microstructural analyses confirmed that the mechanical behavior was governed by the interaction between silica-rich rice husk ash, calcium availability, and alkali activator concentration. Although the achieved compressive strength remained relatively low compared to structural concrete, the results demonstrate the suitability of rice husk ash–based geopolymer mortar for non-structural repair applications, particularly for substrates with low compressive strength, highlighting its potential as a sustainable alternative for concrete rehabilitation.

Lateritic soil has attracted attention as a locally available aluminosilicate source for geopolymer development in tropical regions, including Indonesia. Lateritic soils are typically rich in alumina and iron oxides and can participate in geopolymerization reactions when combined with alkali activators and supplementary silica sources. International studies incorporating lateritic soil into blended geopolymer systems report acceptable mechanical performance and improved sustainability through reduced reliance on industrial by-products (Rangan et al., 2023). In the Indonesian context, research on lateritic soil-based geopolymers remains relatively limited compared to fly ash systems. Available studies suggest that lateritic soil can function as a secondary precursor, particularly under elevated curing conditions that enhance aluminosilicate dissolution. Nevertheless, high mineralogical variability and moisture sensitivity present challenges that require further systematic investigation before large-scale application.

Several studies extend the use of Indonesian local geopolymer precursors beyond conventional concrete and mortar applications. Fly ash-based geopolymers have been successfully applied in soil stabilization, resulting in improved strength and reduced permeability of treated soils (Sutra et al., 2021). In addition, geopolymers derived from Indonesian fly ash demonstrate strong potential for immobilizing heavy metals, significantly reducing leaching under aggressive environmental conditions (Fansuri et al., 2024). These applications highlight the multifunctional nature of geopolymer materials and underscore the broader relevance of Indonesian local materials in addressing both construction and environmental challenges. Freire et al. (2020) explored the use of fly ash– and rice husk ash–based geopolymers for CO_2 capture applications, extending the functionality of geopolymer materials beyond conventional construction uses. The study demonstrates that the aluminosilicate geopolymer matrix derived from industrial and agricultural by-products can effectively interact with CO_2, highlighting its potential role in carbon capture and environmental mitigation strategies. The findings indicate that precursor composition and geopolymer chemistry significantly influence CO_2 uptake behavior, positioning fly ash–rice husk ash geopolymers as multifunctional materials that simultaneously address waste valorization and greenhouse gas reduction. This work underscores the broader sustainability potential of geopolymer systems, particularly in coupling construction materials development with environmental remediation objectives.

Overall, the reviewed literature establishes Indonesian fly ash as the dominant and most viable geopolymer precursor, supported by supplementary materials such as rice husk ash and, to a lesser extent, lateritic soil. While these materials offer substantial sustainability advantages, their performance is strongly governed by source-specific characteristics and processing conditions. This variability underscores the necessity of tailored mix design and curing strategies rather than generalized formulations.

Table 1. Indonesian Local Materials Used as Geopolymer Precursors

No.	Local Material	Source Context	Key Characteristics	Main Findings	Representative References
1	Fly ash	Indonesian coal-fired power plants	SiO_2–Al_2O_3 rich; variable CaO and amorphous content	Reactivity and strength strongly depend on source	Hidayati et al., 2020; Salain et al., 2021
2	Fly ash (multi-source)	Multiple PLTUs	Variation in oxide composition and fineness	Cannot be treated as uniform raw material	Hidayati et al., 2020
3	Fly ash (PLTU-specific)	PLTU Tanjung Jati, PLTU Bolok	Moderate CaO content	High early strength but curing-sensitive	Hartono, 2022; Bastian, 2025
4	Rice husk ash (RHA)	Agricultural residues	High amorphous SiO_2; low Al_2O_3	Moderate replacement improves matrix formation	Ilyas et al., 2022; Olii et al., 2025
5	Rice husk ash (high content)	Agricultural residues	Silica-rich, alumina-poor	Excess replacement reduces strength	Salain et al., 2021; Nurtanto et al., 2020
6	Rice straw ash	Agricultural by-product	High silica content	Requires alumina-bearing material	Rangan et al., 2023
7	Lateritic soil	Tropical soils (Indonesia)	Al_2O_3- and Fe_2O_3-rich	Acceptable performance when blended	Rangan et al., 2023
8	Fly ash–based geopolymer	Indonesian fly ash	Dense aluminosilicate matrix	Effective for soil stabilization	Sutra et al., 2021
9	Fly ash–based geopolymer	Indonesian fly ash	Low permeability matrix	Effective heavy metal immobilization	Fansuri et al., 2024

3.2 Mix Design and Alkali Activator Systems

Mix design is a critical factor governing both fresh and hardened properties of geopolymers developed from Indonesian local materials. Unlike ordinary Portland cement systems, geopolymer mix design in Indonesian studies is largely empirical and strongly influenced by the characteristics of the local precursor materials. Most studies employ fly ash as the primary binder and adjust the liquid-to-solid ratio, precursor blending proportion, and aggregate content to achieve acceptable workability and strength (Salain et al., 2021; Hartono, 2022; Ilyas et al., 2022). A consistent observation across the reviewed literature is that optimal mix proportions vary significantly with fly ash source. Fly ash with higher amorphous content and finer particle size generally requires lower liquid-to-solid ratios, whereas fly ash with higher calcium content or coarser particles demands higher liquid content to ensure sufficient dissolution and homogeneous mixing (Hidayati et al., 2020; Bastian, 2025). These findings emphasize that mix design strategies developed for one Indonesian fly ash source cannot be directly transferred to another without adjustment. Blended precursor systems, particularly fly ash–RHA mixtures, further increase mix design complexity. Several studies report that moderate RHA substitution levels can be incorporated without significant loss of workability or strength, provided that liquid content and activator dosage are adjusted accordingly (Ilyas et al., 2022; Insyira et al., 2023). In contrast, excessive RHA replacement often leads to reduced compressive strength and poor setting behavior due to insufficient alumina availability and imbalanced geopolymer network formation (Olii et al., 2025; Nurtanto et al., 2020).

The alkali activator system plays a central role in controlling geopolymerization kinetics. In Indonesian geopolymer studies, the most commonly used activator combination consists of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Reported NaOH molarities typically range from 8 to 14 M, while Na_2SiO_3-to-NaOH ratios generally fall between 1.5 and 2.5 (Salain et al., 2021; Ilyas et al., 2022; Insyira et al., 2023). Experimental evidence indicates that increasing NaOH concentration enhances aluminosilicate dissolution and accelerates early-age strength development, up to an optimal threshold beyond which workability decreases and microstructural defects may form (Hartono, 2022; Hidayati et al., 2020). Similarly, higher sodium silicate content increases soluble silica availability and promotes gel formation but substantially increases mixture viscosity, which can hinder proper mixing and casting if not carefully controlled (Ilyas et al., 2022). Several studies exploring alternative or supplementary activator sources, including sodium silicate derived from rice husk ash, suggest potential for reducing chemical activator demand while maintaining geopolymer performance. However, such approaches remain limited in number and require further validation for consistency and scalability (Handayani, 2022).

A recurring theme in the reviewed studies is the strong interaction between mix design parameters, activator composition, and curing regime. Mix designs optimized under elevated temperature curing often employ higher activator concentrations and lower liquid-to-solid ratios to maximize early-age strength (Hidayati et al., 2020). However, when similar formulations are applied under ambient curing conditions, rapid setting, incomplete reaction, or reduced long-term strength may occur (Hartono, 2022). Conversely, mix designs intended for ambient curing typically require more conservative activator dosages and higher liquid content to facilitate gradual geopolymerization and reduce cracking risk. These interactions underscore the importance of integrated experimental design that simultaneously considers material characteristics, activator system, and curing regime rather than optimizing each parameter in isolation. Wulandari et al. (2023) examined rice husk ash–based geopolymer mortar incorporating graphene nanosheets, highlighting the combined influence of alkali activator concentration and curing temperature on performance. Increasing NaOH molarity and elevated curing temperatures significantly enhanced compressive strength, with graphene addition promoting matrix densification and improved microstructural integrity.

Microstructural analyses confirmed the formation of a denser aluminosilicate gel with reduced granularity, indicating the potential of nano-additives to improve the mechanical performance of agricultural ash–based geopolymers, albeit with continued reliance on thermal curing. Qomaruddina et al. (2019) examined the influence of calcium oxide–containing materials, including lime, gypsum, and carbide waste, on the setting time of geopolymer and conventional concrete pastes. The study shows that geopolymer paste produced from low-calcium fly ash exhibits relatively longer hardening time, which is strongly affected by both alkali activator molarity and calcium addition. Increasing NaOH molarity from 8 M to 12 M prolonged the setting time of geopolymer paste, whereas the incorporation of calcium-rich additives accelerated setting due to enhanced early-age reaction kinetics. In comparison, conventional cement paste consistently demonstrated longer setting times than geopolymer systems. These findings highlight the dual role of calcium in geopolymer systems, where controlled CaO addition can be used to tailor setting behavior, particularly for applications requiring adjustable workability and early-age performance.

The reviewed literature demonstrates that geopolymer mix design using Indonesian local materials is inherently material-specific and context-dependent. While general parameter ranges can be identified, optimal formulations must be tailored to individual fly ash sources, blended precursor systems, and targeted curing conditions. The lack of standardized mix design guidelines remains a key challenge for broader implementation of geopolymer technology in Indonesia.

Table 2. Mix Design Parameters and Alkali Activator Systems

No.	Precursor System	NaOH Concentration (M)	Na_2SiO_3/NaOH Ratio	Liquid/Solid Ratio	Representative References
1	Fly ash	8–12	1.5–2.5	0.35–0.45	Salain et al., 2021
2	Fly ash (multi-PLTU)	10–14	~2.0	0.35–0.40	Hidayati et al., 2020
3	Fly ash	~10	2.0–2.5	~0.40	Hartono, 2022
4	Fly ash + RHA	8–12	1.5–2.0	0.38–0.45	Ilyas et al., 2022
5	Fly ash + RHA (high content)	~10	~2.0	~0.40	Olii et al., 2025
6	Fly ash + rice straw ash	10–12	~2.0	~0.40	Nurtanto et al., 2020
7	Fly ash + RHA	8–12	~2.0	~0.42	Insyira et al., 2023
8	Fly ash + alternative activator	~10	Variable	~0.40	Handayani, 2022

3.3 Curing Regimes and Their Influence on Geopolymer Performance

Curing regime is one of the most influential parameters governing geo-polymerization kinetics and the resulting performance of geopolymers developed from Indonesian local materials. The reviewed literature shows that two main curing approaches are predominantly adopted: ambient curing and elevated temperature curing. The choice between these approaches is closely linked to practical constraints, target applications, and the characteristics of the precursor materials, particularly fly ash composition. In national studies published in Sinta-indexed journals, ambient curing is the most frequently employed method, reflecting real construction conditions in Indonesia and limited access to controlled thermal curing facilities (Salain et al., 2021; Hartono, 2022; Ilyas et al., 2022). Ambient curing is typically conducted at room temperature (approximately 25–30 °C) with minimal humidity control, allowing geo-polymerization to proceed gradually over extended curing periods. In contrast, a number of international studies involving Indonesian materials employ elevated temperature curing to accelerate geo-polymerization reactions. Elevated curing commonly involves temperatures ranging from 60 to 80 °C applied during the early stages of curing, often for 24 to 72 hours (Hidayati et al., 2020; Rangan et al., 2023). This approach is widely reported to enhance early-age strength development and improve matrix densification.

Studies adopting ambient curing consistently report slower strength development compared to thermally cured specimens. Nevertheless, several Indonesian investigations demonstrate that fly ash–based geopolymers can achieve satisfactory compressive strength at later ages when mix design and alkali activator composition are appropriately optimized (Salain et al., 2021; Hartono, 2022). This gradual strength gain is attributed to slower dissolution of aluminosilicate species and progressive formation of geopolymer gel under ambient conditions. The effectiveness of ambient curing is strongly influenced by precursor characteristics. Fly ash with higher amorphous content and lower calcium oxide concentration generally exhibits better performance under ambient curing, whereas fly ash with elevated CaO content may show incomplete geo-polymerization or mixed reaction products if curing conditions are not carefully controlled (Hidayati et al., 2020; Bastian, 2025). Similar trends are observed in blended fly ash–RHA systems, where ambient curing requires conservative RHA replacement levels to maintain mechanical performance (Ilyas et al., 2022; Olii et al., 2025).

Elevated temperature curing is widely reported to significantly enhance early-age geo-polymerization by accelerating aluminosilicate dissolution and polycondensation reactions. Comparative studies involving fly ash from multiple Indonesian power plants demonstrate that curing at 60–80 °C substantially increases compressive strength within the first few days of curing (Hidayati et al., 2020). Similar improvements are reported in geopolymer systems incorporating rice husk ash, rice straw ash, and lateritic soil, where thermal curing promotes rapid gel formation and microstructural densification (Rangan et al., 2023; Nurtanto et al., 2020). Despite these benefits, several studies caution against excessive curing temperature or prolonged thermal exposure. Rapid moisture loss and differential shrinkage may induce microcracking and negatively affect long-term durability (Hidayati et al., 2020). Furthermore, elevated curing conditions may not be feasible for large-scale or in-situ applications in Indonesia due to energy consumption and logistical constraints.

Comparative assessment of ambient and elevated curing regimes reveals a clear trade-off between early-age performance and practical applicability. Elevated curing is effective for laboratory-scale studies and precast elements where controlled conditions can be maintained. In contrast, ambient curing is more representative of in-situ construction practices in Indonesia, despite slower strength development (Salain et al., 2021; Hartono, 2022). Several studies indicate that mix designs optimized under elevated curing conditions may perform poorly when transferred directly to ambient curing environments, particularly when high alkali activator concentrations are employed (Hartono, 2022). These findings underscore a key limitation in the existing literature, where curing effects are often evaluated without systematically accounting for interactions with mix design and precursor variability. Yilmaz et al. (2024) investigated the mechanical and durability performance of low-calcium fly ash–based geopolymer mortars under different curing temperatures and durations. The results demonstrate that elevated-temperature curing significantly enhances compressive and flexural strength, particularly at longer curing times, with the optimum performance achieved at 80 °C. Durability assessments, including water absorption, void ratio, freeze–thaw resistance, and high-temperature exposure, indicate that improved microstructural densification accompanies thermal curing. Microstructural analyses using SEM, supported by XRD and TGA results, confirm that higher curing temperatures promote a denser geopolymer matrix, highlighting the critical role of initial curing conditions in governing both strength development and long-term durability of low-calcium fly ash geopolymers.

Overall, the reviewed literature establishes curing regime as a decisive factor controlling geopolymer performance using Indonesian local materials. While elevated temperature curing enhances early-age strength and accelerates reaction kinetics, ambient curing remains more relevant for practical implementation. The lack of systematic comparative studies employing identical mix designs under different curing regimes represents a critical research gap that must be addressed to advance geopolymer technology in Indonesia.

Table 3. Curing Regimes Applied in Indonesian Geopolymer Studies

No.	Precursor System	Curing Regime	Typical Conditions	Main Effects on Performance	Representative References
1	Fly ash	Ambient	~25–30 °C, up to 28 days	Gradual strength development	Salain et al., 2021
2	Fly ash (PLTU-specific)	Ambient	Room temperature	Sensitive to CaO content	Hartono, 2022
3	Fly ash + RHA	Ambient	28 days	Acceptable strength at moderate RHA	Ilyas et al., 2022
4	Fly ash + RHA (high content)	Ambient	28 days	Strength reduction at high RHA	Olii et al., 2025
5	Fly ash (multi-PLTU)	Elevated	60–80 °C, 24–72 h	Significant early-age strength gain	Hidayati et al., 2020
6	Fly ash + rice straw ash	Elevated	~60 °C	Accelerated geopolymerization	Nurtanto et al., 2020
7	Fly ash + lateritic soil	Elevated	60–80 °C	Improved gel formation	Rangan et al., 2023
8	Fly ash systems	Ambient vs elevated	Comparative	Trade-off: early strength vs practicality	Hidayati et al., 2020

3.4 Mechanical, Durability, and Microstructural Performance

Mechanical performance, particularly compressive strength, remains the primary indicator used to evaluate geopolymer systems developed from Indonesian local materials. Across the reviewed studies, fly ash–based geopolymers demonstrate compressive strength levels that are comparable to, and in some cases exceed, those of conventional OPC-based materials when mix design, activator composition, and curing regime are appropriately optimized (Salain et al., 2021; Hartono, 2022; Hidayati et al., 2020). However, a wide dispersion of reported strength values is observed, even among studies employing similar activator systems. This variability is largely attributed to differences in fly ash source, calcium oxide content, amorphous phase proportion, and particle fineness (Hidayati et al., 2020; Bastian, 2025). Studies involving fly ash from specific Indonesian power plants consistently highlight

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the importance of source-specific characterization to avoid misleading performance expectations (Hartono, 2022). In blended precursor systems, particularly fly ash–RHA mixtures, moderate RHA replacement levels generally maintain or slightly improve compressive strength due to enhanced silica availability, while excessive replacement leads to strength reduction caused by alumina deficiency and disrupted geopolymer network formation (Ilyas et al., 2022; Olii et al., 2025; Insyira et al., 2023). Similar mechanical trends are reported in systems incorporating rice straw ash and other silica-rich agricultural residues (Nurtanto et al., 2020; Rangan et al., 2023).

Durability-related properties of Indonesian geopolymers have received increasing attention, particularly in relation to aggressive environmental exposure and environmental remediation applications. Fly ash–based geopolymers are reported to exhibit superior resistance to sulfate and acidic environments compared to OPC-based materials, which is attributed to their denser aluminosilicate matrix and reduced calcium content (Sutra et al., 2021). Several international studies demonstrate that Indonesian fly ash–based geopolymers effectively immobilize heavy metals, significantly reducing leaching under aggressive conditions (Fansuri et al., 2024). This capability positions geopolymers as promising materials for environmental applications, including contaminated soil stabilization and waste encapsulation. Nevertheless, systematic long-term durability data under tropical exposure conditions-such as high humidity and wet–dry cycling-remain limited. Hikmah et al. (2024) investigated the combined use of rice husk ash and zeolite as precursor materials in ecofriendly geopolymer mortar, focusing on their effects on setting time, density, and compressive strength. The study shows that the mixed ratio of rice husk ash and zeolite significantly influences both fresh and hardened properties, where appropriate blending improves compressive strength while maintaining acceptable setting characteristics. Zeolite addition contributes to microstructural modification and density variation, indicating its potential role as a supplementary aluminosilicate source. These findings highlight that controlled precursor blending is essential for optimizing the performance of environmentally friendly geopolymer mortar systems.

Microstructural analyses using SEM, XRD, and FTIR consistently confirm the formation of an amorphous aluminosilicate gel as the primary binding phase in geopolymers derived from Indonesian fly ash (Hidayati et al., 2020; Rangan et al., 2023). Elevated temperature curing accelerates gel formation and reduces the fraction of unreacted precursor particles at early ages, while ambient curing promotes more gradual microstructural evolution. In blended systems containing RHA, additional silica modifies gel chemistry and contributes to matrix densification when replacement levels are controlled. However, excessive silica content may hinder complete geopolymerization due to insufficient alumina availability, consistent with observed reductions in mechanical performance (Ilyas et al., 2022; Olii et al., 2025). These microstructural observations are in close agreement with reported mechanical and durability outcomes. Meiliana et al. (2026) investigated the compressive strength characteristics of rice husk ash–based geopolymer concrete by varying the alkali activator ratio between sodium silicate and sodium hydroxide. The results indicate that geopolymer performance is strongly governed by activator proportion, where an optimized $Na_2SiO_3/NaOH$ ratio produced compressive strength exceeding that of conventional concrete at 28 days. While lower activator ratios resulted in reduced strength compared to normal concrete, the optimal geopolymer mixture achieved a significant strength improvement, demonstrating that rice husk ash can function effectively as a geopolymer precursor when appropriate activator balance is employed.

Taken together, the reviewed literature indicates that mechanical strength, durability, and microstructural development of Indonesian geopolymers are governed by a complex interaction between precursor characteristics, mix design parameters, activator composition, and curing regime. Studies that evaluate these aspects in isolation often report inconsistent or non-transferable results, highlighting the need for integrated experimental frameworks.

Table 4. Mechanical, Durability, and Microstructural Performance of Geopolymers Based on Indonesian Local Materials

No.	Precursor System	Performance Aspect	Key Observations	Curing Regime	Representative References
1	Fly ash	Compressive strength	Comparable to OPC under optimized mix	Ambient / Elevated	Salain et al., 2021
2	Fly ash (multi-PLTU)	Strength variability	Strong dependence on ash source	Ambient / Elevated	Hidayati et al., 2020
3	Fly ash (PLTU-specific)	Early-age strength	High early strength but curing-sensitive	Elevated	Hartono, 2022
4	Fly ash + RHA	Mechanical performance	Moderate RHA beneficial; high RHA detrimental	Ambient	Ilyas et al., 2022
5	Fly ash + RHA	Sustainability–strength balance	Improved sustainability with controlled strength	Ambient	Olii et al., 2025
6	Fly ash + rice straw ash	Compressive strength	Requires alumina-bearing precursor	Elevated	Nurtanto et al., 2020
7	Fly ash + lateritic soil	Mechanical and durability	Acceptable performance with thermal curing	Elevated	Rangan et al., 2023
8	Fly ash-based geopolymer	Durability	Improved sulfate and acid resistance	Ambient	Sutra et al., 2021
9	Fly ash-based geopolymer	Environmental performance	Effective heavy metal immobilization	Ambient / Elevated	Fansuri et al., 2024
10	Fly ash-based geopolymer	Microstructure	Dense aluminosilicate gel formation	Ambient / Elevated	Hidayati et al., 2020

4. DISCUSSIONS

4.1 Key Challenges in Indonesian Geopolymer Development

Despite significant progress, several challenges continue to limit the broader adoption of geopolymers developed from Indonesian local materials. The most prominent challenge is the high variability of fly ash sourced from different coal-fired power plants. Differences in chemical composition, amorphous phase content, calcium oxide level, and fineness result in inconsistent geopolymer reactivity and mechanical performance, even when similar mix designs and activator systems are applied (Hartono, 2022; Bastian, 2025). Another major challenge relates to curing practice. While elevated temperature curing consistently enhances early-age strength, it is often impractical for in-situ construction due to energy demand and logistical constraints. Conversely, ambient curing—more representative of Indonesian construction conditions—frequently results in slower strength development and higher sensitivity to mix design and precursor characteristics (Salain et al., 2021; Ilyas et al., 2022). This trade-off complicates the transition of geopolymer technology from laboratory-scale research to field implementation.

The use of supplementary agricultural ashes, particularly rice husk ash, also presents challenges. Although RHA offers sustainability benefits and enhances silica availability, improper proportioning can disrupt the Si/Al balance, leading to reduced mechanical performance and incomplete geopolymerization (Olii et al., 2025; Nurtanto et al., 2020). Ensuring consistent ash quality and controlled processing remains a practical barrier.

4.2 Identified Research Gaps

The reviewed literature reveals several critical research gaps that warrant attention. First, there is a lack of standardized classification schemes for Indonesian fly ash based on reactivity rather than solely on oxide composition. Such classification would facilitate more transferable mix design strategies and improve comparability across studies (Hidayati et al., 2020). Second, systematic comparative studies that evaluate identical mix designs under different curing regimes are limited. Many studies investigate curing effects in isolation, making it difficult to decouple the influence of curing from that of mix composition and precursor variability (Hartono, 2022; Rangan et al., 2023).

Third, long-term durability data under tropical exposure conditions-such as high humidity, temperature fluctuation, and wet-dry cycling-remain scarce. Although several studies demonstrate promising durability and environmental performance, extended exposure testing is necessary to support structural and infrastructure applications (Sutra et al., 2021; Fansuri et al., 2024). Finally, the integration of mechanical, durability, and microstructural analyses within unified experimental frameworks is still limited. Many studies report these aspects separately, restricting the development of mechanistic understanding and predictive performance models.

4.3 Future Research Directions

Future research on geopolymers based on Indonesian local materials should prioritize integrated experimental frameworks that simultaneously consider precursor characterization, mix design, activator system, curing regime, and performance evaluation. Developing reactivity-based classification systems for Indonesian fly ash would represent a critical step toward standardized and transferable geopolymer formulations. Greater emphasis should also be placed on ambient-curing-optimized geopolymer systems, as these are more compatible with Indonesian construction practices. Research into alternative activator sources derived from agricultural waste, such as sodium silicate produced from rice husk ash, offers potential pathways to reduce chemical activator demand and improve sustainability (Handayani, 2022).

Beyond structural applications, expanding research into non-structural and environmental uses, including soil stabilization and heavy metal immobilization, aligns strongly with Indonesia's infrastructure and environmental remediation needs (Sutra et al., 2021; Fansuri et al., 2024). Such applications may serve as practical entry points for broader geopolymer adoption while long-term structural performance data continue to mature.

Table 5. Key Challenges, Research Gaps, and Future Perspectives in Indonesian Geopolymer Research

Aspect	Key Issues Identified	Implications for Future Research
Precursor variability	Heterogeneous fly ash properties across PLTUs	Development of reactivity-based classification
Mix design transferability	Source-specific optimization required	Material-tailored mix design guidelines
Curing practice	Dependence on elevated curing	Ambient-curing-optimized systems
Supplementary materials	Si/Al imbalance with high RHA content	Controlled blending and quality assurance
Durability	Limited long-term tropical exposure data	Extended durability and field testing
Methodological integration	Fragmented performance evaluation	Unified mechanical–durability–microstructure studies

5. CONCLUSION

This review synthesizes findings from thirty peer-reviewed national and international studies on the development of geopolymers using Indonesian local materials. Fly ash from Indonesian coal-fired power plants is confirmed as the dominant and most viable geopolymer precursor, while supplementary materials such as rice husk ash and other agricultural by-products can enhance sustainability and performance when used in controlled proportions. The performance of Indonesian geopolymers is governed by a complex interaction between precursor characteristics, mix design parameters, alkali activator systems, and curing regimes. Elevated temperature curing consistently improves early-age strength, whereas ambient curing-more representative of practical construction conditions in Indonesia-results in slower but progressive geo-polymerization. Variability in precursor properties, particularly fly ash, remains the primary challenge to achieving consistent and transferable performance. Despite substantial research progress, key gaps remain in standardization, long-term durability assessment under tropical conditions, and integration of mechanical, durability, and microstructural analyses. Addressing these gaps through systematic and context-specific research will be essential for advancing geopolymer technology toward reliable, scalable, and sustainable applications in Indonesia and similar developing regions.

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