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Geopolymer as a Low-Carbon Structural Solution for Disaster Risk Mitigation: A Systematic Review Based on the IPCC Perspective

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ABSTRAK

Krisis iklim dan peningkatan intensitas bencana alam menuntut solusi terpadu yang mencakup dimensi struktural dan sosial. Industri konstruksi, terutama pemanfaatan semen Portland (OPC), bertanggung jawab atas sekitar 7–8% emisi karbon global, dan kerentanan infrastruktur terhadap bencana semakin meningkatkan risiko bagi masyarakat. Studi ini mengisi celah literatur dengan mengintegrasikan inovasi material rendah karbon, khususnya beton geopolimer, dengan strategi kesiapsiagaan berbasis komunitas dalam kerangka mitigasi risiko bencana dan kebijakan iklim IPCC. Tinjauan pustaka sistematis dilakukan terhadap 35 publikasi terpilih dari Scopus, ScienceDirect, Google Scholar, dan laporan IPCC AR6. Temuan menunjukkan bahwa beton geopolimer dapat mengurangi emisi karbon hingga 97%, memiliki ketahanan tinggi terhadap panas, gempa bumi, dan lingkungan korosif, serta cocok untuk infrastruktur di wilayah rawan bencana. Strategi sosial seperti edukasi, simulasi evakuasi, dan penguatan kelembagaan lokal terbukti efektif dalam meningkatkan ketangguhan masyarakat. Studi ini mengusulkan kerangka "*dual-resilience*" yang memadukan kekuatan struktural dengan kapasitas sosial, yang relevan untuk diarusutamakan dalam kebijakan pembangunan berkelanjutan di Indonesia.

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geopolymer, carbon emissions, community preparedness, disaster mitigation, IPCC, low carbon concrete

ABSTRACT

The climate crisis and increasing intensity of natural disasters demand an integrated solution encompassing both structural and social dimensions. The construction industry, particularly the use of Portland cement (OPC), accounts for approximately 7–8% of global carbon emissions, and the vulnerability of infrastructure to disasters further elevates risks for communities. This study addresses a gap in the literature by integrating low-carbon material innovations, specifically geopolymer concrete, with community-based preparedness strategies within the framework of disaster risk mitigation and IPCC climate policy. A systematic literature review was conducted on 35 selected publications from Scopus, ScienceDirect, Google Scholar, and IPCC AR6 reports. Findings indicate that geopolymer concrete can reduce carbon emissions by up to 97%, exhibits high resistance to heat, earthquakes, and corrosive environments, and is suitable for infrastructure in disaster-prone areas. Social strategies such as education, evacuation drills, and strengthening local institutions have proven effective in enhancing community resilience. This study proposes a "dual-resilience" framework that combines structural strength with social capacity, which is relevant for mainstreaming in sustainable development policies in Indonesia.

1. INTRODUCTION

Indonesia is one of the nations with the highest levels of disaster risk in the world as it is located in the overlap of three large tectonic (Eurasian, Indo- Australian, and Pacific) (Hutchings et al., 2021). According to Global Assessment Report on Disaster Risk Reduction (UNDRR, 2022), Indonesia is at a high risk in the occurrence of earthquakes, tsunamis, floods, and even volcanic eruption. National Disaster Management Agency (BNPB) data reveal that there were over 3,000 per annum disasters on average between 1999 and 2019, and the figures have been on the rise due to inundations and severe weather conditions identified as a result of climate change. The Yogyakarta, Padang, and Palu earthquakes (2006, 2009, and 2018) demonstrated that the country infrastructure and population are highly vulnerable to complications, which leads to considerable economic costs and loss of lives.

Disasters have become more severe and intricate in the world due to the climate crisis. The Intergovernmental Panel on Climate Change (IPCC AR6, 2022) has affirmed that the construction industry produces 786 percent of all the carbon emissions across the world, building of Ordinary Portland Cement (OPC) being one of the largest contributors to these figures. In Indonesia, infrastructure development has resulted in a rapid development of the economy through the national economic acceleration agenda that has seen OPC consumption increasing by several folds putting the sector in a conflict between the requirement to strike development and national emission reduction objectives (Net Zero Emission 2060). To conform to this trend, a number of the countries of Southeast Asia have turned to looking into low-carbon alternative material, such as geopolymer concrete, as another aspect of the movement to construction sustainability. Liu et al. (2024) established a study that geopolymer mix designs, which were based on industrial waste, could greatly decrease the carbon emissions, and Amar et al. (2024) highlighted that geopolymers could become the environmentally friendly material that pursues the global decarbonization directions. However, due to poor technical standards, poor regulatory provisions, and low awareness and understanding in industrial sector adoption has not been attained in Indonesia.

From a social perspective, the vulnerability of Indonesian communities remains high, mainly due to limited disaster education, low self-efficacy, and weak local institutions. The study by Qiu et al. (2023) also revealed that preparedness regarding hazards is low in prone communities due to lack of sufficient disaster education, lack of self-efficacy, and poor local institutions. Another issue identified by Rusmana et al. (2024) is the difficulties associated with the community-based mitigation implemented in coastal regions since the social structures and the lack of resources are likely to serve as obstacles to its application. These results strengthen the fact that social resiliency is important in achieving the success of risk mitigation, although physical frameworks are prepared to survive any natural calamity. Therefore, the discrepancy between technical-structural solutions and the community capacity building can be defined as one of the critical gaps that need to be filled..

Since 2015, studies on low-carbon construction in Southeast Asia have become more prominent. In Vietnam (Dung et al., 2020) and Malaysia (Nuruddin et al., 2016), research has been done on how to expound geopolymer materials made using fly ash and slag as environmental-friendly alternatives that can effectively mitigate emissions as well as increase the mechanical performance. Somna et al. (2017) in Thailand tested the methodology of using rice husk ash and volcanic ash locally as suggested as alternative raw materials and obtained good results associated with sustainable practices. In the meantime, Indonesia is starting to investigate the application of industrial waste of geopolymers, but the research is still at a severe compartmental level of laboratory work (Indriyantho et al., 2023). The tendency indicates a robust local move towards the use of low-carbon construction materials, which is consistent with the promises of the Paris Agreement and Net Zero goals.

Nevertheless, most research studies continue to pay more attention on the technical side of geopolymers, including compressive strength, durability and emission reduction, whereas there is a scarcity of research on integration with the community-based social strategies. In fact, the literature on Community-Based Disaster Risk Reduction (CBDRR) emphasizes that community adaptive capacity is a key determinant of risk mitigation success (Qiu et al., 2023; Rusmana et al., 2024). Therefore, this study offers a theoretical contribution by developing a dual-resilience framework that integrates geopolymer material innovation with CBDRR strategies. Practically, this study applies in the further development of Indonesian National Standards (SNI) of geopolymers as well as enhancement of mainstreaming of CBDRR in the national and local development planning (RPJMN/RPJMD). Therefore, this research aims to fill in the information in literature gaps, and also offer a scientific touching point in sustainable disaster risk mitigation policies within Indonesia.

2. METHODOLOGY

2.1 Research Design

The present research has used a Systematic Literature Review (SLR) method to define, value, and generalize the available empirical evidence about the use of geopolymer as a low-carbon material in construction and measures to handle community preparedness in a disaster risk reduction.

Moreover, the integration of findings from the literature studies that were performed in the other areas, like the area of materials engineering, environmental policy, and disaster management, in an adequate and meaningful way justified the use of the SLR approach. This was carried out following the PRISMA (Preferred Reporting Items to Systematic reviews and meta-analyses) protocol to establish the traceability and accountability of the review (Page et al., 2021).

2.2 Literature Search Strategy and Data Sources

The Scopus, science Direct, and Google Scholar were utilized to perform the literature search and to focus on the articles addressing the geopolymer concrete within the context of climate change, reduction of carbon emissions, and prevention of disasters.. The search formulas employed included: geopolymer concrete-heit kword join - AND -

carbon emission seismic resistance -AND- climate adaptation - AND- disaster resilience. Only articles from 2015 to 2025 were in the publication period, and English and Indonesian languages were used as considered languages. The document types were journal articles, policy reports, technical studies or books that were in full-text and peer-reviewed documents or publications of official entities such as the IPCC and UNEP.

In order to guarantee the presence of transparency and the accessibility of tracing, every phase in the literature search and sifting procedure was recorded via the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) framework.

2.3 Inclusion and Exclusion Criteria

Inclusion Criteria:

1) Studies presenting empirical data or systematic reviews related to geopolymer or community preparedness strategies.
2) Publications with full-text access.
3) Research conducted in areas with high levels of disaster vulnerability, such as earthquakes, wildfires, floods, or coastal regions.

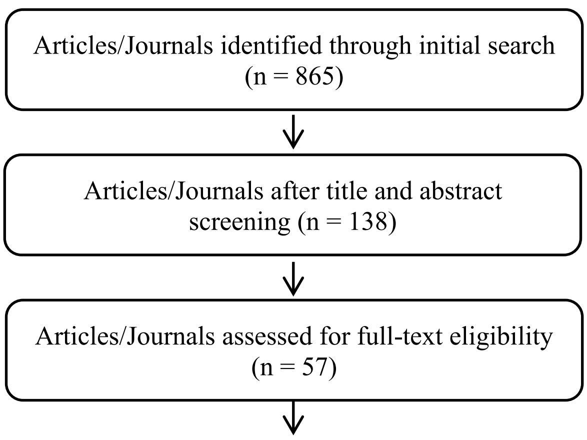
Exclusion Criteria:

1) Papers in the form of opinion pieces, editorials, or similar publications that have not undergone peer review.
2) Studies addressing only structural mitigation without discussing social adaptation.
3) Duplicate studies retrieved from cross-database searches.

2.4 Literature Selection Process

The selection process consisted of four stages:

1) Identification: A total of 865 articles were retrieved from the initial database search.
2) Screening: By reviewing titles and abstracts, 138 articles were shortlisted.
3) Eligibility: Full-text assessment reduced the pool to 57 relevant articles.
4) Final Inclusion: Based on methodological appraisal, only 35 articles were deemed suitable for the final analysis.
5) This process is illustrated in the PRISMA flow diagram (Figure 1).



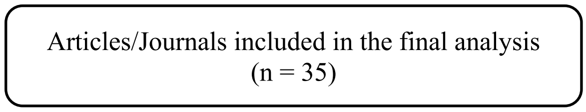


Figure 1. PRISMA Flow Diagram

2.5 Data Analysis Methods

The analysis was conducted thematically by categorizing the studies into five main sub-theme categories::

1) Carbon emissions and environmental impacts of geopolymers
2) Mechanical properties and durability
3) Field implementation of geopolymers
4) Adoption challenges and national policies
5) Community preparedness strategies

The determination of these five sub-theme categories was based on a combination of theoretical and empirical criteria. Theoretically, the categories correspond to the core dimensions discussed in the IPCC framework and recent scientific reviews that link low-carbon materials to disaster resilience (Shrestha & Rajeev, 2021; Ling et al., 2022; Qiu et al., 2023). Empirically, these categories emerged through pattern identification during the screening and coding process of 35 eligible studies, where recurring research themes were consistently found across these five domains. This categorization approach enables a structured synthesis that integrates both technical performance evidence (carbon reduction and structural durability) and social dimensions (community preparedness and policy adoption) within the context of disaster risk mitigation.

The data were manually coded and cross-verified using the double-coding method by two independent researchers to ensure consistency of interpretation.

2.6 Study Validation and Quality Assessment

The quality assessment of the studies was conducted using the JBI Critical Appraisal Checklist, adapted for quantitative, qualitative, and mixed-methods research. The appraisal was carried out by two independent reviewers, and only studies with high and moderate credibility scores were included in the analysis.

Out of 57 eligible full-text articles, 35 studies met the minimum quality threshold 18 were rated as *high quality* and 17 as *moderate quality* while low-quality studies were excluded due to incomplete methodological descriptions or lack of peer-review validation. The inclusion of these 35 validated studies ensured the reliability and robustness of the synthesis results.

Furthermore, IPCC AR6 documents were used as primary secondary sources to triangulate scientific findings with globally recognized policy frameworks, thereby enhancing the credibility of the interpretations and strengthening the linkage between low-carbon material innovation and disaster risk reduction strategies.

3. SYNTHESIS OF FINDINGS FROM THE LITERATURE REVIEW

This study analyzes 35 selected scientific articles to investigate two main aspects: the potential of geopolymer as a low-carbon structural material and community preparedness strategies for disaster response. The findings are organized thematically and accompanied by a critical analysis.

3.1 Carbon Emissions and Environmental Impact

Most recent studies indicate that the use of geopolymer concrete can substantially reduce carbon emissions by approximately 40-80% compared to Ordinary Portland Cement (OPC), although the exact values vary depending on the type of raw materials and the curing methods applied (Shrestha & Rajeev, 2021; Ben Ali et al., 2024). The main reason for this reduction lies in the absence of the *clinker calcination* process, which in OPC production contributes to nearly 60–70% of total CO_2 emissions due to limestone decomposition and high-temperature fuel combustion. In contrast, geopolymer concrete utilizes industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), and locally available volcanic ash, which require no additional calcination and thus significantly lower embodied carbon (Provis, 2018; IPCC AR6, 2022).

From an environmental standpoint, the use of geopolymer concrete offers dual benefits. First, it directly reduces greenhouse gas emissions by minimizing reliance on limestone and fossil fuels. Second, it promotes circular economy practices through the utilization of industrial and natural waste materials that would otherwise contribute to land and air pollution. In the Indonesian context, the abundant availability of volcanic ash presents a sustainable and locally sourced precursor that can substitute imported or coal-based materials, reducing both environmental and logistical footprints (Sahu et al., 2024).

Therefore, the environmental impacts discussed in this study refer to both the *positive environmental contributions* of geopolymer concrete such as emission reduction, waste utilization, and resource efficiency and the *contextual environmental opportunities* derived from local raw material potential, particularly volcanic ash. This sustainable shift positions geopolymer technology as a viable pathway toward achieving low-carbon and disaster-resilient construction aligned with Indonesia's Net Zero Emission 2060 target.

Table 1. Comparison of OPC and Geopolymer Concrete Characteristics

Aspect	OPC Concrete	Geopolymer Concrete
CO_2 Emissions	High (7-8% globally)	Low (↓40-97%)
Compressive Strength	20-50 MPa	40-70+ MPa
Temperature Resistance	<300ºC	Up to 800ºC
Chemical Resistance	Susceptible	Resistant to Sulfates/Chlorides
Material Source	Limestone, Sand	Fly Ash, Slag, Volcanic Ash
SNI or Standards	Available	Not yet available in Indonesia

Source: IPCC AR6 (2022), Zhang et al. (2020), McLellan et al. (2011), Provis & van Deventer (2014), Lahoti et al. (2019), Salmabanu et al. (2021).

3.2 Mechanical Properties and Durability

Recent experimental findings confirm that geopolymers exhibit high compressive strength (>60 MPa), stability at temperatures up to 800°C, and resistance to sulfates and chlorides (Luhar et al., 2021; Yasin et al., 2024). The study by Ling et al. (2022) further reinforces that geopolymers are more stable in marine environments compared to OPC, making them relevant for coastal infrastructure in the aftermath of tidal flooding. Nevertheless, several studies report performance inconsistencies due to variations in local materials and limitations in process control (Zaki et al., 2024). This indicates that successful implementation in Indonesia will largely depend on the development of Indonesian National Standards (SNI) and the technical capacity of laboratories.

3.3 Global Implementation

One of the most prominent examples is the construction of Brisbane West Wellcamp Airport in Queensland. This project is recognized as the world's first large-scale construction project to utilize geopolymer concrete in an exceptionally high volume more than 40,000 cubic meters, equivalent to approximately 100,000 tons of concrete. The geopolymer material used was developed by Wagners under the commercial name Earth Friendly Concrete (EFC), consisting of fly ash and ground granulated blast furnace slag (GGBFS) without using cement clinker. The concrete was applied in the construction of the apron, taxiways, and various other structural elements.

The outcomes of this implementation were highly significant: geopolymer concrete succeeded in reducing carbon emissions by approximately 6,600 tons of CO_2 compared to OPC-based concrete of the same volume. The project won a strategic milestone of gaining more use of geopolymer concrete as the Concrete Institute of Australia gave it the award of Engineering Project of the Year 2015. Institutional support was also provided by the CRC for Low Carbon Living through collaboration with Standards Australia in preparing guidelines and efforts to integrate geopolymer into national construction standards. Technical findings from this project indicated that, in addition to environmental advantages, geopolymer concrete demonstrated structural performance comparable to, and in some cases exceeding, conventional concrete, particularly in terms of compressive strength, high-temperature resistance, and long-term durability (Zhang et al., 2020; Lahoti et al., 2019).

Beyond the airport project, geopolymer concrete has also been implemented in public buildings such as the Global Change Institute Building at the University of Queensland. This building became the world's first public structure to use precast geopolymer concrete panels as a major part of its structural system, marking a technological transition from experimental scale to actual architectural application.

In South Asia, several initiatives in India and Nepal have explored the application of geopolymer concrete, particularly for housing construction designed to be earthquake-resistant. Although the scale is not yet comparable to projects in Australia, geopolymer has been considered in the context of sustainability, industrial waste utilization, and carbon emission reduction in the construction sector. Verma et al. (2022), in a publication in *Crystals*, highlighted that fly ash and slag in India hold substantial potential as raw materials for geopolymer, being not only environmentally friendly but also economical and suitable for local climatic conditions. However, as of now, there are no explicit policies within the National Building Code of India or Nepal formally recommending geopolymer concrete as a primary building material. Thus, implementation in these countries remains at a limited and experimental stage, although national policy directions indicate openness toward low-carbon alternatives.

3.4 Community Preparedness Strategies

The analysis of eight journals identified five main strategies commonly employed, namely community education and training, implementation of evacuation drills, participatory risk mapping, strengthening of local institutional capacity, and integration of local cultural values. These strategies have been consistently emphasized across studies conducted in Indonesia, Japan, and other disaster-prone countries.

Table 2. Summary of Studies on Community Preparedness Strategies (n=8)

Study	Country	Main Strategy	Effectiveness
Lestari et al. (2021)	Indonesia	Disaster Education	Improving Literacy
Shaw et al. (2013)	Jepang	Evacuation Drill	Enhanced Response
Kusuma & Hidayat (2019)	Indonesia	Risk Mapping	Local Strengthening
Fitria et al. (2020)	Indonesia	Volunteer Institutions	Rapid Response
Putra & Santoso (2022)	Indonesia	Integration of Cultural Values	Accepted by the Community
Haynes et al (2021)	Australia	Social Resilience and Awareness	Strengthened Adaptive Behavior
Parvin et al. (2020)	Bangladesh	Community-Based DRR Programs	Increased Local Participation
Hutagalung (2023)	Indonesia	Leadership and Institutional Capacity	Improved Adaptive Capacity

However, the effectiveness of these strategies is highly dependent on the local social and cultural context. For example, highly hierarchical social structures or low levels of trust in the government can hinder active community engagement.

3.5 Integration of Structural and Social Solutions

Structurally, geopolymer concrete has been proven to possess high mechanical strength and exceptional thermal stability. Zhang et al. (2020) noted that the compressive strength of geopolymer concrete can exceed 70 MPa under heat curing conditions, while Lahoti et al. (2019) demonstrated its resistance to extreme temperatures up to 800°C, making it highly suitable for areas prone to wildfires or earthquakes that trigger secondary fires. Furthermore, the use of fly ash and slag as raw materials positions geopolymer concrete as a low-carbon solution, with the potential to reduce emissions by up to 97% compared to conventional OPC concrete (McLellan et al., 2011; IPCC, 2022).

However, resilient buildings cannot be fully effective without communities equipped with preparedness capacities. Research conducted by Shaw et al. (2013) and Prabowo & Widiyanto (2020) revealed that disaster education, evacuation drills, and the strengthening of local institutions such as village preparedness groups have been shown to significantly enhance community response capacity. As a result, communities equipped with adequate disaster education are more likely to respond more quickly and effectively during major disasters, thereby reducing the number of casualties.

The fusion of both solutions can be seen in the idea of resilient infrastructure which does not just mean the ability of the physical strength of the buildings but of social ability to face the threats. According to Global Assessment Report (UNDRR, 2022), disaster risk reduction is best achieved in case local risks are considered during the building design and engages residents in the planning process and all the way to implementation (UNDRR Global Assessment Report 2022). In this respect, the technical solution of geopolymer as a construction material, especially in terms of low emission development, will also be a statement of concern; on the sustainability of the early warning mechanisms and preparedness by allowing community participation through involvement.

Nogueira et al. (2023) also pointed out that infrastructure constructed by the means of transdisciplinary team which comprises of civil engineering, environmental science and sociology stands better placed to sustain disaster and recover faster in comparison to infrastructure which relies on what is referred to as technical strength. This once again concludes the need to incorporate the concept of technology and social aspects to national and local programs to lower disaster risks. This is to say that application of geopolymer as a social solution and structures as well that should be applied should be regarded as one integrated thing. The physical infrastructure resilience fostered by the technical approach and the social responsiveness, flexible and sustainable communities fostered by the social approach make each other stronger. The collaboration of both provides a pathway toward resilient, equitable, and sustainable development amidst escalating disaster risks driven by climate change and rapid urbanization.

3.6 SWOT Analysis of Geopolymer Concrete Adoption

The SWOT analysis was conducted to evaluate the strengths, weaknesses, opportunities, and threats in adopting geopolymer concrete as a climate- and disaster-resilient construction material.

Table 3. SWOT Analysis of Geopolymer Concrete for Disaster Risk Mitigation in Indonesia

Strength	Weakness	Opportunity	Threat
Low carbon emissions (↓40–97%) (Provis & van Deventer, 2014; McLellan et al., 2011).	The absence of SNI or national regulations governing geopolymer formulation (Hardjito et al., 2002).	Support from the IPCC and global policy direction toward low-carbon materials (IPCC AR6, 2022).	Risk of declining fly ash availability due to energy decarbonization and the reduction of coal-fired power plants (McLellan et al., 2011).
High compressive strength and resistance to temperatures up to 800°C (Zhang et al., 2020; Lahoti et al., 2019).	Variation in fly ash quality across regions and dependence on coal-fired power plants (Ben Ali et al., 2024).	The national Net Zero Emission program provides incentives for material innovation.	The dominance of the market by conventional cement producers hinders the adoption of alternative materials.
Resistance to sulfates, carbonation, and seawater (Salmabanu et al., 2021).	Lack of laboratory infrastructure and trained technicians at the local level (Davidovits, 2015).	Potential applications in large-scale infrastructure projects (new capital city, logistics corridors, bridges, etc.).	Weak synergy between academia, industry, and government in research and technology commercialization.
Potential integration with community preparedness strategies (dual resilience).	Lack of awareness among stakeholders and construction institutions regarding the benefits of geopolymer.		

The SWOT analysis above shows that geopolymer has strong potential as an adaptive material for climate change and disaster resilience in Indonesia. However, the main barriers still stem from structural aspects, namely the absence of national standards, supply chain constraints, and limited technical capacity. Policy opportunities such as the IPCC's recommendations and the national Net Zero Emission program need to be leveraged through fiscal incentives, integration into strategic infrastructure projects, and the enhancement of technical education for industry stakeholders. Mitigation of threats to fly ash supply should also be addressed through the diversification of local raw materials and the development of alternative formulations based on volcanic ash.

4. CONCLUSION AND RECOMMENDATIONS

This study synthesizes findings from 35 recent scientific studies (2015–2025) and concludes that the integration of technological solutions through geopolymers with social strategies based on CBDRR represents the most effective approach to strengthening disaster resilience in Indonesia. Thematically, the key insights of this review can be summarized as follows:

1. Emissions and Environmental Impact
   Geopolymer concrete can reduce carbon emissions by 40–97% compared to OPC, depending on the type of raw materials and curing methods (Shrestha & Rajeev, 2021; Ben Ali et al., 2024). This aligns with the IPCC AR6 (2022) recommendation, which emphasizes clinker substitution and the utilization of industrial by-products.
2. Technical Performance and Durability
   Recent studies show that geopolymer concrete achieves compressive strength >70 MPa, remains stable at temperatures up to 800°C, and is resistant to sulfates, carbonation, and chloride ion intrusion (Yasin et al., 2024; Ling et al., 2022). With these characteristics, geopolymers hold strong potential as an ideal material in earthquake-prone and coastal flood-prone areas.
3. Field Implementation
   Case studies from the Toowoomba Bypass in Australia and earthquake-resistant housing projects in India and Nepal demonstrate that geopolymer concrete can be applied both in large-scale infrastructure projects and at the community level (Verma et al., 2022; Zaki et al., 2024). However, adoption in Southeast Asia remains limited due to the absence of explicit regulations.
4. Community Social Strategies
   Five key approaches education, evacuation drills, risk mapping, strengthening local institutions, and cultural integration have proven effective in enhancing risk literacy and community adaptive capacity (Haynes et al., 2021; Qiu et al., 2023).
5. Adoption Challenges
   The main barriers include the absence of Indonesian National Standards (SNI) for geopolymers, dependence on fly ash from coal power plants that are projected to decline due to the energy transition, variability in material quality, and low awareness among industry players and regulators (Sahu et al., 2024).

Based on the synthesis of these findings, this study recommends:

1. Regulation and Standardization
   The government should develop Indonesian National Standards (SNI) for geopolymers, grounded in the latest research (2015–2025), covering formulation, mechanical testing, durability, and disaster resilience aspects.
2. National Pilot Projects
   The implementation of geopolymer concrete pilot projects in earthquake-prone areas such as Nusa Tenggara, Sulawesi, and Papua should serve as learning platforms as well as proof-of-concept foundations for scaling up larger projects.
3. Integration into RPJMN/RPJMD
   Community preparedness strategies should be explicitly incorporated into national and regional development planning, including RPJMN and RPJMD documents, as part of strengthening social resilience.
4. Cross-Sector Collaboration
   Establish a triple helix consortium (academia–industry–government) with NGO support to accelerate applied research, technology downstreaming, and evidence-based policy formulation.
5. Diversification of Local Raw Materials
   Prioritize research on the use of volcanic ash and biomass as alternatives to fly ash (Sahu et al., 2024), to ensure long-term sustainable material availability and support the development of low-carbon construction materials.

Thus, strengthening building structures using geopolymers while simultaneously enhancing community preparedness can serve as a solid foundation for realizing sustainable and disaster-resilient development in Indonesia. Moreover, the use of geopolymers as environmentally friendly materials not only increases the durability of buildings against natural disasters such as earthquakes, floods, and corrosive environments, but also supports national carbon reduction efforts toward Indonesia's Net Zero Emission target. On the social side, enhancing community capacity through education, evacuation simulations, and strengthening local institutions reinforces community resilience.

In the context of Indonesia, the application of the dual resilience approach is highly relevant due to the country's strong social capital and community-based culture. The communal characteristics of Indonesian society such as *gotong royong* (mutual cooperation), collective decision-making, and high levels of social solidarity provide a solid foundation for integrating technical and social resilience. The use of geopolymer materials can be aligned with community-based initiatives such as disaster-resilient villages (*Desa Tangguh Bencana*) and green construction movements, where community members actively participate in material utilization, housing reconstruction, and local monitoring. Therefore, the dual resilience approach can be practically implemented through collaborative frameworks that combine structural innovation (e.g., low-carbon geopolymer construction) with social empowerment (e.g., disaster education, institutional strengthening, and participatory planning). This alignment ensures that technological advances in sustainable materials are supported by culturally rooted social systems, enabling disaster-resilient development that fits Indonesia's local contexts.

By combining the structural strength of innovative materials with the social capacity of communities, the concept of "dual resilience" provides a strategic framework to achieve sustainable development that is safe, resilient, and adaptive to climate change.

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