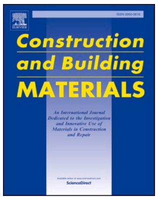
Construction and Building Materials 409 (2023) 133888

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Review

Systematic review on geopolymer composites modified with nanomaterials and thin films: Enhancing performance and sustainability in construction

Abdulaziz Alaskar [a], Muhammad Sarmad Mahmood [b], Roz-Ud-Din Nassar [c], Osama Zaid [b,*], Fadi Althoey [d], Mohamed M. Arbili [e]

[a] Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 12372, Saudi Arabia
[b] Department of Civil Engineering, Swedish College of Engineering and Technology, 47070 Wah Cantt, Pakistan
[c] Department of Civil and Infrastructure Engineering at American University of Ras Al Khaimah, United Arab Emirates
[d] Department of Civil Engineering, College of Engineering, Najran University, Najran, Saudi Arabia
[e] Department of Technical Civil Engineering, Erbil Technical Engineering College, Erbil Polytechnic University, 44001 Erbil, Iraq

ARTICLE INFO

Keywords:
Geopolymer Composites
Nanomaterials
Thin Films
Characterization techniques
Hardened properties

ABSTRACT

Concrete, a common building material, mostly contains cement. Cement production utilizes much energy, depletes natural resources, and emits carbon dioxide. Efforts are being made to create concrete without cement. In this regard, developing geopolymer composite as a viable novel construction material creates a better substitute for sustainable building practices. This study presents a systematic review to examine recent and ongoing research to explore the impacts of various nanomaterials (NMs) and thin films (TF) on geopolymer composite's hardened properties and microstructure. In this context, thin films, specialized layers of material applied to the surface of green concrete, typically with a thickness ranging from nanometers to micrometers, are considered. These films may contain various NMs to enhance or modify the concrete's properties and microstructure. The importance of characterization techniques such as XRD (X-ray diffraction), SEM (Scanning Electron Microscopy), and FTIR (Fourier-transform infrared spectroscopy) is emphasized, as they play a crucial role in understanding the properties and performance of geopolymer nanomaterials and thin films. A large database, including the key attributes of geopolymer composites with NMs and thin films, was created using data from more than 158 published studies. Furthermore, the research identifies current accomplishments, limitations, and future research goals in nanomaterials and thin films for green concrete. These advancements are expected to significantly impact emerging fields, with potential applications ranging from advanced coatings for corrosion protection and fire resistance to functional electronic devices and sensor surfaces. This comprehensive review contributes to the advancement of green concrete technology and the development of sustainable construction materials. The insights gained from this study and the created database provide valuable knowledge for researchers and industry professionals, facilitating the adoption of NMs and thin films to improve the performance and sustainability of concrete in construction.

1. Introduction

The most frequently used construction material worldwide is conventional concrete [1], and its demand is driven by several qualities, such as how easy it is to acquire, how resistant it is to heat and water, and how adaptable it is to different sizes and forms [2,3]. Conventional

---

Abbreviations: NM, Nano Material; CS, Compressive Strength; STS, Split Tensile Strength; FS, Flexural Strength; MK, Metakaolin; MCNT, Multiwall carbon nanotube; CNT, Carbon nanotube; µm, Micrometer; NC, Nano clay; N-A-S-H, Nitrogen alumina silicate hydrate; C-A-S-H, Calcium alumina silicate hydrate; C–S–H, Calcium-silicate-hydrate; O-H, Oxygen-hydrogen; S-O-S, Silica-oxygen-silica; A-O-S, Alumina-oxygen-silica; NCC, Nano calcium carbonate; NFA, Nano fly ash; nm, Nanometer; NMK, Nano-metakaolin; NA, Nano-Al_2O_3; NS, Nano-SiO_2; NT, Nano-TiO2; NGP, Nano glass powder; NZ, Nano zinc oxide; GO, Graphene Oxide; GNP, Graphene Nanoplatelets; AS, Alumina silicate; FA, Fly ash; GPC, Geopolymer Concrete; GGBFS, Ground granular blast furnace slag; FTIR, Fourier transform infrared; XRD, X-ray diffraction; SEM, Scanning electron microscope; PFA, Palm oil fuel ash; PVA, Polyvinyl alcohol; RCPT, Rapid chloride permeability test; RHA, Rice husk ash; SF, Silica Fume; SH, Sodium hydroxide; SS, Sodium silicate.

* Corresponding author.

E-mail address: Osama.zaid@scetwah.edu.pk (O. Zaid).

https://doi.org/10.1016/j.conbuildmat.2023.133888
Received 25 July 2023; Received in revised form 27 September 2023; Accepted 18 October 2023

concrete is used in the construction of almost all civil engineering projects. Globally, concrete is projected to be utilized the most after water. Its main component, OPC production, is expected to shift between 3.7 and 4.4 billion tons by 2050, with a 2.5% annual growth rate from 2.3 billion tons in 2005 to 3.5 billion tons in 2020 [4]. Unfortunately, OPC production accounts for 5–8% of all manufactured carbon-based greenhouse gas emissions worldwide, or 0.6–0.8 kg of CO_2 produced for every kilogram. Three major sources of CO_2 emissions are present during OPC production: burning of fuel (approximately 325 kg/ton), decarbonization of limestone (about 525 kg/ton), and electrical energy consumption (about 50 kg/ton) [2]. Approximately 80 kW-hours of electricity and 1500 kg of raw materials are needed to produce one ton of OPC. Because of this, researchers have focused their efforts on reducing OPC usage by creating other forms of binders, ultimately reducing carbon dioxide emissions [3,5].

The development of novel materials and the investigation of previously utilized materials' undiscovered qualities have been made possible by advances in science and technology [6]. This similar evolutionary approach has been applied to construction materials. In this regard, Geopolymer technology, invented by Davidovits in France in 1970, is a practical, appropriate substitute for ordinary concrete [7]. The formation of inorganic alumina-silicate polymers involves the alkaline synthesis of various aluminosilicate materials and other waste products rich in silicon and aluminum. These waste products may include fly ash (FA), ground granulated blast furnace slag (GGBFS), metakaolin (MK), and rice husk ash (RHA). Combining these materials through alkaline activation creates a family of alumina-silicate polymers [8]. Utilizing these waste materials in geopolymer composite production, which needs raw materials with a high aluminosilicate content, lowers the environmental pollution burden. Due to the abundance of these wastes and the increasing need for affordable housing, using these waste products will be advantageous from a sustainability point of view. Geopolymer Concrete (GPC) has undergone substantial worldwide advancements, and it may someday be the best green building material. The use of GPC can aid in ensuring the long-term survival of concrete technology and the building industry [6,9].

Compared to Portland Cement Concrete (OPC), Geopolymer is an eco-friendly substance emitting around 70% less carbon dioxide. This is primarily due to its extensive utilization of waste materials in its composition [4]. Geopolymer materials have increased compressive strength, superior fire resistance, little creep, minimal shrinking, increased durability, and resilience to acidic conditions [6,10,11]. The combination of GPC consists of the alumina-silicate base binder, coarse and fine fillers, alkali stimulants, and water. Through polymerization, these components lead to robust concrete that is fundamentally like traditional concrete. The geopolymer technology can be applied to 3D printing of concrete, ceramics, and additive manufacturing [12,13].

Heat-curing techniques are frequently employed to accelerate the polymerization process in geopolymers. Nanomaterials (NMs) are more responsive because they have a larger surface area per unit volume. NMs have a microscopic impact on the microstructure of geopolymer composite even without temperature curing. As a result, both hardened concrete and raw concrete exhibit significantly better structural performance. By combining regular Portland Cement, GGBFS, Nano Silica, and Alccofine during room temperature curing, several studies looked to increase geopolymer composite's mechanical performance and durability. Therefore, many researchers emphasize using nanotechnology in geopolymer [14–16].

The scope to alter and restructure the material at the atomic level sizes between 1 and 100 nm is referred to as nanotechnology. It also involves the influence of specific properties and phenomena at this size comparable to those seen in individual atoms and molecules or on a larger scale [13–15]. With unique scientific findings and useful applications, nanotechnology is a thriving area of study that has grown in importance over the past 20 years [16,17]. Recently, attempts have been undertaken to add nanomaterials into geopolymer composites to improve the composition's qualities and create concrete with better performance.

In addition to nanotechnology, recent trends also originate in geopolymer composites with thin films or coatings. Therefore, the preservation of buildings and elements is of utmost importance in civil and construction engineering, where the maintenance and repair of infrastructures have become significant issues [1]. Due to their resistance to dangerous chemicals (such as acids, alkalis, and salts) and harsh environmental factors (such as extremely high or low temperatures, repeated drying and wetting cycles, etc.) in the service environments of civil constructions, thin films are both necessary and advantageous. Recently, a novel class of inorganic thin films that are mostly made of geopolymers has been studied and used to protect the surfaces of structural components made of concrete, steel, and wood.

This systematic review has thoroughly examined the different types of geopolymer composites having nanomaterials and thin films and analyzed and evaluated the impacts on the mechanical and microstructure properties of geopolymer composites by utilizing all previous and recent research in this context. Geopolymer composite, in this context, refers to a composite material that integrates geopolymer binders with nanomaterials and thin films, along with potential reinforcement elements like fibers or particles. The study also assessed the advantages and potential applications of geopolymer composites incorporating nanomaterials and thin films. Furthermore, the importance of each technique in understanding the properties and performance that are used for characterizing, such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and others. Finally, information on recent research findings and advancements, constraints, difficulties, and future research directions are presented.

1.1. *Research significance*

This research article thoroughly reviews the influence of nanomaterials (NMs) and thin films on the functionality of green concrete. To the author's knowledge, previous articles briefly mentioned the impact of NMs on geopolymer composites. Still, this paper provides an in-depth analysis of both nanomaterials and thin films in geopolymer composites.

The aim is to help readers understand the distinctions and significance of these two fields. The study examines recent and ongoing research on the effects of various NMs and thin films on geopolymer composite's hardened and microstructure properties. It compares the advantages of nanomaterials and thin films over conventional geopolymer composites. The importance of each approach in characterizing geopolymer nanomaterials and thin films is emphasized, along with their role in understanding properties and performance through techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). Furthermore, it identifies current research accomplishments, limitations, and future research goals. This knowledge will contribute to the advancement of green concrete technology and the development of sustainable construction materials.

1.2. *Research goals*

The research's main objective is to check the results of earlier investigations and offer an overview of the significance and properties of NM and TF geopolymer composites. A few technical research questions are created, as summarized in Table 1, to focus on the study.

1.3. *Contribution and layout*

The systematic literature review (SLR) enhances previous research efforts and introduces new contributions to Civil and Materials engineering, specifically focusing on geopolymer composites.

Table 1
Research Questions.

Research Questions (RQ)	
RQ1:	What are the different geopolymer composites, nanomaterials, and thin films that researchers mostly consider?
RQ2 (a):	What are the characterization techniques and fundamental properties of nanomaterials Geopolymer Composites?
RQ2 (b):	What are the characterization techniques and fundamental properties of thin film Geopolymer Composites?
RQ3:	What are the recent advancements and the potential future research directions of nanomaterials and thin film geopolymer composites?

- As of early July 2023, 220 significant works about geopolymer composites incorporating nanomaterials and thin films have been identified. This extensive body of research forms a solid foundation for future, more detailed scientific investigations in this field.
- Subsequently, 158 studies meeting the predefined quality criteria were selected, offering valuable data for comparative analysis with similar research.
- Following this, a thorough examination of data from these 158 studies was conducted to identify key ideas and characteristics related to geopolymer composites and their associated nanomaterials and thin films.
- Within this context, a meta-analysis is presented, evaluating the impact of various nanomaterials and thin films on the mechanical and microstructural properties of geopolymer composites, drawing upon the entirety of prior and ongoing research within the field.
- Limitations are defined, and recommendations are made to encourage further research and development in this research area.
- The upcoming sections of the paper are organized as per Taylor et al. [18]'s framework. "Section 02 outlines the meticulous procedures for selecting primary papers for analysis. The outcomes and analysis of all selected primary research are presented in Section 03. Section 04 offers discussions on the previously mentioned research topics and suggestions for further studies. Finally, Section 05 specifies a comprehensive outcome of our findings.

2. Research methodology

In this Systematic Literature Review (SLR), a thorough investigation was undertaken to address the research questions based on the criteria organized by Kitchenham et al. [19]. The review's planning, organization, and reporting stages were meticulously executed through multiple iterations to ensure a comprehensive evaluation. In the initial search of the digital library, 350 items were identified. Employing the inclusion/exclusion criteria detailed in section 2.1 and analyzing the titles, abstracts, and keywords from the search results, the remaining 220 papers were located. Upon comprehensive evaluation of the entire content of these papers against the inclusion/exclusion criteria, 158 publications satisfied the requirements. This methodology aligns with the approach described by Wohlin [20], encompassing both forward and backward snowballing. Before initiating forward snowballing, reverse snowballing was undertaken by scrutinizing the citation lists of all research articles, leading to the discovery of additional articles conforming to the collection criteria. Table 2 describes the online electronic database used for research work.

Table 2
Online Electronic Databases.

Online Electronic Database	URL Address
Science Direct	www.sciencedirect.com/
IEEE Xplore Digital Library	www.ieeexplore.ieee.org/
Springer	www.link.springer.com/
Scopus	www.elsevier.com/solutions/scopus
Web of Science	www.webofscience.com/
MDPI	www.mdpi.com/

2.1. Inclusion and exclusion criteria

The findings must demonstrate a computerized approach to Geopolymer composites that considers nanomaterials and thin films and their characteristics, and they must produce analytical results that take objectives into account. They must be authored in English and published in the peer-reviewed journals. Table 3 lists the main inclusion/exclusion standards.

2.2. Selection results

Initial searches conducted on the titles, abstracts, and keywords within reputable libraries yielded 350 research publications, as depicted in Fig. 1. Following the inclusion/exclusion criteria application, 220 articles were retained in the first phase. Subsequently, the criteria were again applied, resulting in 140 significant studies. The remaining publications were then carefully reviewed while considering the specified criteria. The relevant articles were then employed in a backward and forward snowballing strategy, as described by Wohlin [20], to locate more important papers to include in this SLR as 158.

2.3. Data analysis

The content from the examined articles was categorized into qualitative and quantitative sections to present the study's outcomes regarding the research questions. A systematic review was also executed on the selected articles identified during the screening process.

2.3.1. Publications over time

The primary studies discovered throughout the search procedure were then utilized following the quality rating criteria. The publishing history with the total number of papers is presented in Fig. 2 between July 2013 and July 2023 by the various journals that make up the SLR.

3. Research analysis

Recently, there has been substantial progress in geopolymer composites, focusing on understanding their properties and the influence of nanomaterials and thin films on their performance. Geopolymer composites are increasingly recognized for their potential applications in various industries, including construction and infrastructure, as an alternative to OPC in reducing carbon emissions.

This section examines geopolymer composites' properties and performance and explores how nanomaterials and thin films affect their properties. Each primary research article on geopolymer composites was carefully reviewed, and qualitative and quantitative data relevant to their properties and the influence of nanomaterials and thin films were thoroughly evaluated and presented in detail, as depicted in Tables 5 and 7. The research questions outlined in Table 1 were considered to guide the analysis of these studies.

Table 3
Inclusion-Exclusion Criteria.

Inclusion Criteria	Exclusion Criteria
The manuscript presents analytical information about the objectives and study goals.	Articles that analyze and compare the geopolymer idea
Journal articles that have undergone peer review.	Papers focusing solely on Geopolymer chemistry and modeling
Journal Articles examining Geopolymer composites, their properties, and the influence of nanomaterials in geopolymer composites.	Technical reports or official government papers
Journal Articles examining Geopolymer composites, their properties, and the influence of thin films in geopolymer composites.	Non-English articles

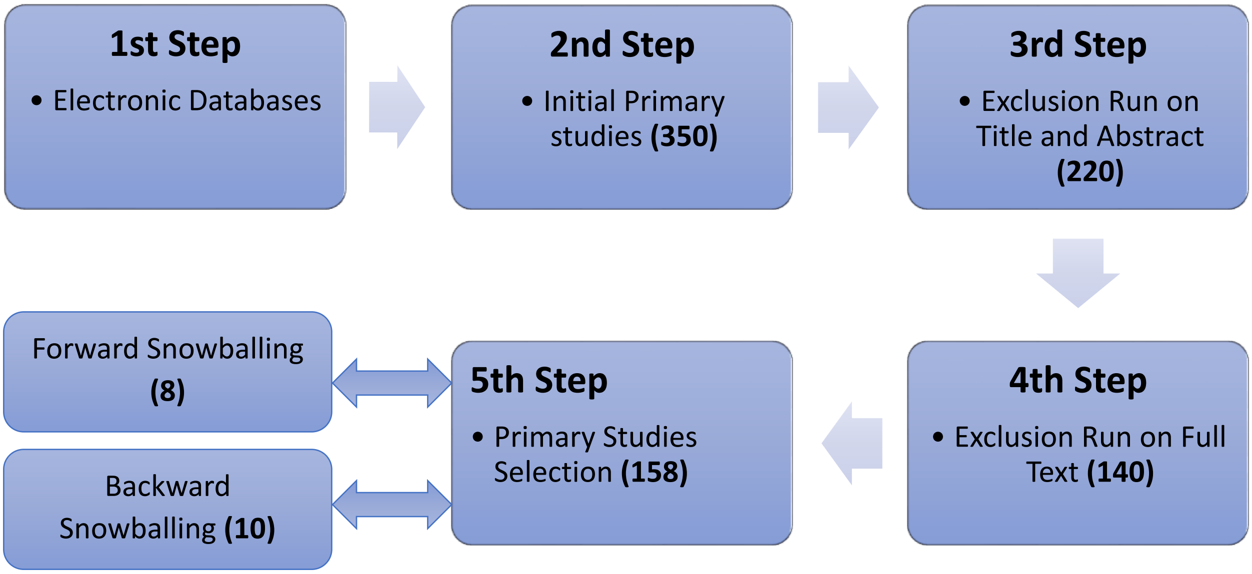


Fig. 1. Primary studies selection process.

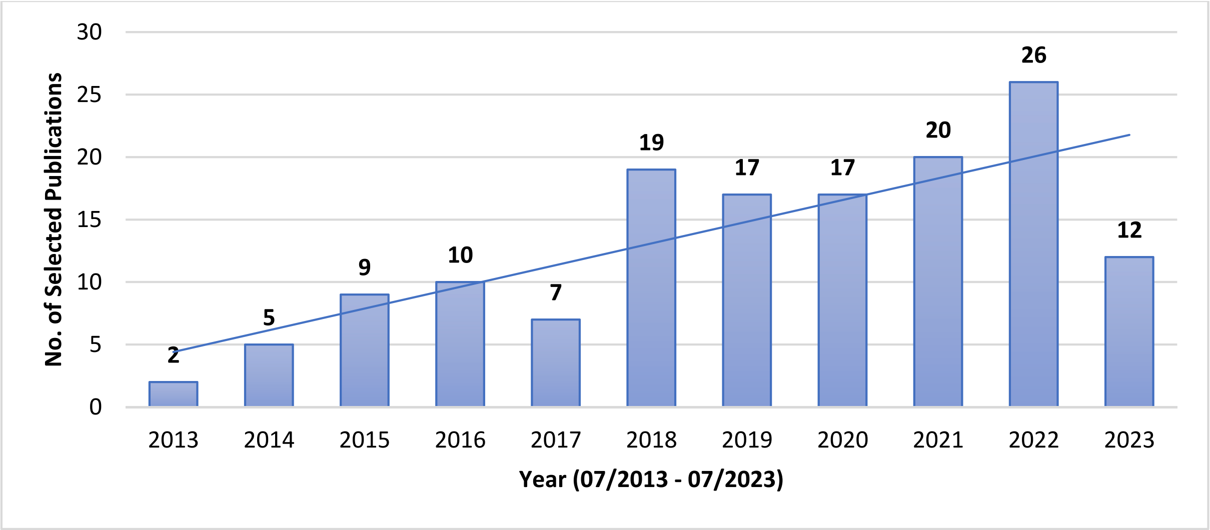


Fig. 2. Publishing history (2013–2023).

Using nanomaterials and thin films, researchers have discovered novel ways to enhance the properties of geopolymer composites. Nanomaterials, such as nanoparticles, nanofibers, and nanotubes, offer the opportunity to enhance geopolymer composites' strength, durability, chemical resistance, and thermal characteristics. Thin films, conversely, provide a nanoscale coating on the surface of geopolymer particles, imparting tailored functionalities and further enhancing the overall performance of the composites.

The synthesis methods and incorporation techniques used for nanomaterials and thin films in geopolymer composites are discussed, along with their impact on the properties of the composites. Furthermore, the influence of nanomaterials and thin films on characteristics such as mechanical strength, microstructure, and surface morphology is thoroughly examined. Fig. 3 presents the flow chart of the systematic review. Additionally, nanomaterials and thin films exhibit unique properties and behaviors when engineered or manipulated at the nanoscale. Table 4 highlights some key distinctive features that make nanomaterials and thin films highly advantageous for various applications.

3.1. *Nano materials geopolymer composites*

Nanomaterials geopolymer composites are innovative materials that combine geopolymer matrices with nanoscale additives or reinforcements [99]. Geopolymers are inorganic materials formed through a chemical reaction between source materials and alkaline activators, offering advantages like high strength and durability. Contrarily, nanomaterials, which are generally 1–100 nm in size, have distinctive features at the nanoscale [66]. These composites harness the nanomaterials' enhanced mechanical, thermal, and electrical characteristics by integrating nanomaterials into the geopolymer matrices. The nanoscale size of the additives or reinforcements enables them to interact more effectively with the geopolymer matrix, resulting in improved overall properties of the composites. This includes increased strength, enhanced thermal stability, improved electrical conductivity, and greater resistance to cracking [90,100,101].

3.1.1. *Characterization techniques*

The primary means by which the addition of different Nano Material

Table 4
Distinctive Features of Nanomaterials and Thin Films at the Nanoscale.

Distinctive Feature	Nanomaterials	Thin Films
High Surface Area-to-Volume Ratio	Nanomaterials exhibit an exceptionally high surface area compared to their volume, enhancing reactivity and interactions with surrounding substances. Valuable for catalysis, adsorption, and sensing applications.	Thin films with nanoscale features offer an extended interface for interactions with their environment, making them valuable for applications such as sensors, coatings, and electronic devices.
Quantum Effects	Quantum mechanical phenomena become pronounced. Quantum confinement and size quantization lead to size-dependent electronic and optical properties. Utilized in displays, quantum dots, and medical imaging.	Nanoscale thin films can exhibit size-dependent optical properties, including quantum confinement effects. These properties are utilized in optical devices, displays, and photovoltaics.
Size-Dependent Properties	Properties vary with size. Mechanical, electrical, and optical characteristics can be tailored by controlling the dimensions of nanoscale structures. This size-dependent behavior is crucial for achieving desired functionalities in devices and coatings.	Thin films are engineered with precise control at the atomic and molecular levels, allowing for tailored material properties and functionalities.
Improved Mechanical Properties	Some nanomaterials, especially nanocomposites, can exhibit superior mechanical properties, such as increased strength and flexibility. These enhancements make them suitable for advanced materials in structural applications.	Thin films with nanoscale surface modifications can have enhanced adhesion properties, contributing to their suitability for protective coatings and advanced materials.

types enhances the performance of geopolymer composites is via the improvement of microstructure. The presence of nanomaterials (NMs) significantly improves the porous structure and the interfacial transition zone (ITZ) through their polymerization reactions [102].

Researchers have examined microscopic phenomena using the SEM, XRD, and Fourier transform infrared (FTIR); detailed references are listed in Table 5.

A material's mechanical, physical, and durability properties are directly influenced by the percentage of voids and porosity within its structure [103]. The most popular SEM, XRD, and FTIR tests were examined in-depth in the following section.

3.1.1.1. Scanning Electron Microscope (SEM). Scanning Electron Microscope (SEM) analysis of organic and inorganic materials may be done on a nanoscale to micrometer (nm) scale. With 300,000x maximum magnification, SEM can take incredibly precise pictures of various materials. SEM was broadly employed to study the impacts of NMs on the morphological enhancement in the geopolymer composites over time by taking pictures with high resolutions of the nano-geopolymer composites [24].

A microstructural analysis of the GGBFS composite that included micro and nano silica was performed by Behfarnia et al. [27]. The composite's microstructure was examined using SEM to measure the effects of incorporating NS (Nano silica), revealing an improvement in the microstructure of the geopolymer composite. This improvement was attributed to the inclusion of NS in the geopolymer matrix, leading to the maturity of supplementary sodium aluminosilicate hydrate (N-A-S-H) gels because of the pozzolanic reaction of NS. Consequently, the tiny void spaces were filled with these additional gels. As the gel adheres to the particles, it effectively fills the gaps between them and binds them together. Like this, Ibrahim et al. [43] conducted experimental studies to determine the influence of incorporating NS on the strength and microstructure of geopolymer concrete, as illustrated in Fig. 4. The concrete samples NS concentrations of 0, 1, 2.5, 5, and 7.5 %. SEM was performed on the centrally adjusted blocks of the 25 mm cubes of geopolymer composites to examine their shape and elemental content. The comparison between the composites and the virgin samples without any NS dosages revealed an enhancement in the microstructure of the latter due to the addition of NS. It was further suggested that the optimal dose for achieving a denser and more uniform microstructure in the composites was 5% of NS with the fewest possible NS particles that had not yet undergone a chemical reaction. The claim that Silica and Aluminum are the essential elements in the polymerization reaction helped to support this conclusion. Introducing Nano silica (NS) to the geopolymer matrix leads to chemical interactions among Silica, Aluminum, and alkaline solutions. These interactions, which are greatly influenced by the concentrations of the alkaline solutions, play a crucial role in enhancing the microstructure of the GPC. Including NS facilitates an increase in silica and accelerates the geo-polymerization process. However, it was found that adding NS at doses of 2.5 and 7.5 %, respectively, resulted in only partial pore filling. Therefore, at these greater concentrations, the NS did not affect the microstructure or strength of the geopolymer concrete.

Furthermore, The SEM analysis of cured FA/GGBFS-based Geopolymer (GPFS) samples with varying amounts of Polydimethylsiloxane (PDMS) revealed (Fig. 5) that the addition of PDMS resulted in increased surface roughness and a relatively loose structure in GPFS-3.0 compared to GPFS-0. The unreacted fly ash and slag particles in GPFS-3.0 indicated that PDMS might hinder the reaction between the precursor powder and alkali activator, leading to larger pores and reduced compressive strength. The SEM analysis findings were consistent with the pore test results, showing increased micron-sized pores with higher PDMS content. Cracks observed in the images were likely due to the weaker structure caused by PDMS addition and potential artificial or drying factors during sample preparation [97].

Like this, geopolymer mortar composites' microstructure enhancement was seen despite using several NM kinds, and this can be confirmed by studies conducted by Huseien et al. [52] and Samadi et al. [58], which utilized field emission scanning electron microscopy (FESEM) to scan the structural properties.

Recently, Wulandari et al. [84] used graphene nanosheets in rice husk-based geopolymer composite and checked their morphological properties. The SEM study aimed to investigate two main aspects: the placement of graphene on the geopolymer matrix and the formation of crystals by geo-polymerization. Samples were examined under two conditions: one without adding graphene (GNs), cured at 40°Celsius with 6 M of NaOH, and the other with 4% GNs, cured at 80°Celsius with 14 M of NaOH. The SEM examination results, shown in Fig. 6, compared the geopolymer mortar with and without GNs.

The comparison revealed that the geopolymer mortar lacking GNs displayed several holes, making it appear porous and susceptible to fractures. On the other hand, GNs resulted in a denser mortar structure, especially with the higher curing temperature of 80°Celsius. The GNs effectively filled the pores and empty spaces in the geopolymer mortar due to the impact of the elevated curing temperature. Overall, adding GNs improved the geopolymer mortar's microstructural characteristics and a denser surface.

Moreover, researchers incorporate various NMs and check their properties, whose details are mentioned in Table 5. A suite of advanced techniques has facilitated the comprehensive investigation of nanomaterials' influence on geopolymer composites. Scanning Electron Microscope analysis, capable of achieving up to 300,000x magnification, has enabled precise imaging of nanomaterial-geopolymer interactions,

Table 5
Major findings from the research articles regarding the addition of Nanomaterials.

Ref.	Type of composite	Type of Nanomaterial	Fresh Properties Tests		Hardened Properties Tests			Durability Properties Tests	Micro structure Properties Tests	Major Findings
			W	S	CS	SPT	FS			
[21]	Fly Ash	NS			✓		✓	✓	✓	NS added at 0.5, 1.0, 2.0, and 3.0%. 1.0 % NS significantly improved properties, porosity (27%) and water absorption (35%), density (15%), compressive strength (27%), and flexural strength (28.8%).
[22]	Fly Ash	NCP					✓	✓	✓	NCP added at 1.0, 2.0, and 3%. The addition of 2.0 wt% improved properties, density (10%), porosity (25%), and flexural (25%).
[23]	Fly Ash	NCP			✓		✓	✓	✓	NCP added at 1.0, 2.0, and 3%. Adding 2.0 wt% improved properties, compressive strength (23%), and flexural strength (20%).
[24]	Fly Ash	NS	✓		✓	✓	✓			Adding 6% nano-silica to fly ash-based geopolymer concrete eliminates the need for high-temperature activation and improved structural performance.
[25]	Fly Ash	NS			✓	✓	✓	✓		Severe durability check: 5% sulfuric acid, 5% magnesium sulfate, and 3.5% seawater. NS added improved overall properties (20%).
[26]	Fly Ash with GGBFS	NS	✓	✓	✓				✓	0.5%, 1.0%, 1.5%, 2.0% and 2.5% NS and SF. The optimum % = 1.5 of the SF and NS content. Improved compressive strength (up to 20%).
[27]	GGBFS	NS	✓		✓			✓	✓	0.5%, 1%, 3% and 5% NS, 10% MS. 5% NS = Slump reduction: 82%; 3% NS and 10% MS = CS increased: 11% and 28%, respectively.
[28]	Fly ash with Rice Husk Ash	NS	✓		✓	✓	✓	✓		The 28-day compressive strengths containing RHAs ranged from 36.0 to 38.1 MPa due to the improved microstructure and denser matrix and were comparable to those of RAGCs made with NS.
[29]	Fly Ash	CNS	✓	✓	✓	✓	✓	✓	✓	CNS: 0%, 4%, 6%, 8% and 10% fly ash. Optimum CNS 6% increased properties up to 20% compared to control.
[30]	Fly Ash with GGBFS	NC			✓	✓	✓			Optimum 6% dosage of NC for both FA and GGFBS. Improved CS, SPT, and FS of FA and GGFBS by 25.9%, 29.02%, 36.80%, 46.54%, 50.72%, and 48.29%, respectively.
[31]	GGBFS	NA, NC, NS	✓		✓			✓		1, 2, and 3% by wt. 3% NS, up to 2% NA and up to 2% NC improved CS (by 20%) and durability properties.
[32]	Fly Ash with GGBFS	NC, CNT			✓		✓	✓		Optimum 2.5% NC blended with 0.01% CNTs improved CS and FS by 90.2% and 34%, respectively.
[33]	GGBFS	MWCNT			✓			✓	✓	MWCNTs added 0.0, 0.1, 0.2, 0.3, and 0.4% by weight. Optimum: XRD = 0.1 and 0.4%, FTIR = 0.1 and 0.4%, SEM = 0.1%, water absorption = 0.1%, drying shrinkage reduced = 0.1 by 92%, CS increased = 0.1% and 0.2% by 24.6% and 12.97% respectively.
[34]	GGBFS	NT			✓		✓	✓	✓	0.5% dosage improved CS and FS by 9%, reduced shrinkage by 27%, and reduced porosity by 19.8% at 28 days.
[35]	Fly Ash and GGBFS	WGNP			✓				✓	5% optimum WGNP increased CS by 16% and enhanced microstructure properties.
[36]	GGBFS	NS, NM			✓	✓	✓		✓	0, 2%, 4%, 6%, and 8% of NS and NM. Optimum: NM 6% and NS 4%. Increased CS, SPT, and FS by up to 30%.
[37]	Fly Ash	NS, NC	✓		✓		✓		✓	1, 2, and 3% by wt. Improved CS and FS by 65 and 45 %, respectively.
[38]	Fly Ash	NZn + NS	✓		✓	✓	✓	✓	✓	Incorporating the ZnO-SiO_2 hybrid in GPC improved properties by up to 30%, indicating its potential for creating biodeterioration-resistant concrete with enhanced mechanical and structural performance.
[39]	Fly Ash and GGBFS	NS	✓	✓	✓			✓	✓	Optimum NS: 2% increased CS by up to 40% and decreased porosity from 30.5% to 27.2%. Notably, higher slag content has higher CS.
[40]	Fly Ash	GNP			✓		✓		✓	Optimum 1% GNP improved CS and FS by 1.44 and 2.16 times, respectively.
[41]	Fly Ash	NT			✓	✓	✓	✓	✓	NT 1–5% by wt. Dosage. Optimum = 5%. Improved CS, SPT, and FS by 54.96%, 32.63%, and 22.22%, respectively.
[42]	Fly Ash with OPC	NS	✓		✓	✓	✓	✓		Optimum 15% FA with 1% NS improved all hardened and durable properties, notably CS, by 38%.
[43]	Natural Pozzolan	NS	✓	✓	✓				✓	A 5% addition of nano-silica (NS) increased compressive strength (CS) by 18%, as confirmed by SEM analysis, revealing a homogeneous and denser microstructure with fewer unreacted particles.

(*continued on next page*)

Table 5 (*continued*)

Ref.	Type of composite	Type of Nanomaterial	Fresh Properties Tests		Hardened Properties Tests			Durability Properties Tests	Micro structure Properties Tests	Major Findings
			W	S	CS	SPT	FS			
[44]	Natural Pozzolan	NS	✓		✓		✓		✓	NS dosages: 1%, 2.5%, 5% and 7.5%. Optimum: 5% NS improved CS and FS by 35%.
[45]	Natural Pozzolan	NS			✓				✓	Dosage replacement NS up to 7.5%. The optimum 5% increased CS by 18% compared to the control mix.
[46]	Fly Ash	NS, NT, CNT			✓					Dosages: NS = 0.75%, 3%, 6%; CNT = 0.02%; NT = 1%. NT 1% showed promising results, increasing CS by 46.65%.
[47]	Fly Ash	NS			✓			✓	✓	NS dosage = 0%, 2%, 4%, 6%, 8%. Optimum = 8% NS.
[48]	Metakaolin	NS			✓			✓		0.5% and 1% NS incorporated with 10, 20, 30, and 40% metakaolin. Optimum: 30% MK with 0.5% NS.
[49]	GGBFS	NS	✓		✓	✓	✓	✓		Adding 2%, NS demonstrated a strength increase of 17.65% to 18.94% across various testing ages.
[50]	Fly Ash and GGBFS	NS			✓			✓	✓	The optimum 2% dosage of NS with 1% steel fiber increased CS by up to 25%. Also enhancing durability properties.
[51]	Fly Ash and GGBFS with OPC	NS	✓		✓			✓	✓	Optimum Dosage: 2% NS. CS increased by 63%. Strength loss due to acid attack: 9–11% (as compared to 30–41%).
[52]	Fly Ash and GGBFS	WGNP	✓	✓	✓	✓	✓	✓	✓	5% optimum dosage: CO_2 reduction = 6%; CS increased = 16%, lowered binder cost = 3.4%; lowered energy consumption = 1.3%.
[53]	Fly Ash	NM			✓				✓	NM Dosage incorporated: 0%, 2%, 4%, 6%, 8% and 10%. Optimum = 4%. Increased CS by 70–80%.
[54]	Fly Ash	NT			✓	✓		✓	✓	Optimum dosage NT = 5%. Max CS and SPT = 53 MPa and 6.8 MPa, respectively. Also enhanced water absorption by up to 10%.
[55]	Silica Fume and GGBFS	NS	✓		✓			✓	✓	NS at 2% and 4% dosages and SF of 5%, 7.5% and 10%. Optimum = 2% NS, 5% SF.
[56]	Fly Ash and GGBFS	NS			✓				✓	NS = 0–3%. 2.5 NS yields CS by up to 50% and showed no cracks under 30–800 °C heat treatment.
[57]	Fly Ash	MWCNT			✓			✓	✓	MWCNTs dosage = 0.05–0.2% of the wt. of FA. Optimum = 0.15% increased CS by 70%. Even a minimal amount (0.05%) of MWCNTs significantly reduced the formation of microcracks, as detected by Acoustic Emission.
[58]	Fly Ash and GGBFS	WGNP	✓	✓	✓	✓	✓	✓	✓	Enhanced CS by 16% and reduced CO_2 by 6% at 5% WGNP. Also, enhanced microstructure properties (XRD, SEM, FTIR).
[59]	Metakaolin	NS			✓			✓	✓	2% optimum dosage of NS, increased CS by 25%. Also, adding the NS (3%) could improve the efflorescence.
[60]	Fly Ash and Metakaolin	NS	✓		✓		✓	✓	✓	Polyvinyl alcohol (PVA) fiber and NS at 0–1.2% and 0–1%, respectively. Enhanced strengths by 68%; however, the combined effect reduces strength. Optimum dosage: PVA = 0.8%, NS = 1% combined.
[61]	Metakaolin	MWCNT			✓		✓		✓	MWCNT dosages: 0, 0.5, 1% wt. Optimum: 0.5% increased CS and FS by 32% and 28%, respectively.
[62]	Fly Ash	NA			✓		✓		✓	Nano Al_2O_3 Dosages %: 1,2 3. Optimum = 2% wt. Increased CS and FS from 23.9 MPa to 29.4 MPa and 3.03 MPa to 4.38 MPa, respectively.
[63]	Fly Ash	NC			✓		✓		✓	Dosages % = 1, 2, 3, NC dosage of 1 and 3% increased CS by up to 33%.
[64]	Fly Ash and GGBFS with OPC	NS			✓				✓	NS dosages = 1–3%. 2 % increased CS from 62 MPa to 72 MPa. The SEM images revealed that adding nano-silica enhanced the reaction product's compactness.
[65]	Fly Ash	NT	✓		✓			✓	✓	NT dosages = 1, 3, 5%. CS increased by 22% at 5% NT (56 days).
[66]	Volcanic Tuff	NS			✓			✓	✓	Incorporated volcanic tuff with NS (1, 2, 3%), MS (1, 3, 5%), and Styrene-Butadiene Latex (SBL) (5, 10, 15%). Optimum NS and SBL: 2% and 5%, respectively. MS optimum: 5% and 3% for Na_2SiO_3 + NaOH and sole NaOH-activated, respectively
[67]	Metakaolin	NS					✓	✓	✓	1% NS optimum yields higher strength (25.8%), higher density (15%), and lower porosity (18.8%).
[68]	Metakaolin	NS		✓	✓				✓	Maximum CS obtained at NS 1.5. Also, SEM photographs illustrate a more compact microstructure of the geopolymer.
[69]	GGBFS	MWCNT			✓	✓			✓	Nanomaterials increased properties (CS: 50%, SPT: 68%). SEM analysis confirms the formation of a dense and compact microstructure
[70]	GGBFS, Silica Fume, Metakaolin, and Waste glass	MWCNT			✓			✓	✓	MWCNT: 0.01 up to 0.09% by weight. Optimum: 0.07% MWCNT. XRD, FTIR, and SEM analyses highlighted the absence of ettringite compounds, even in later curing

(*continued on next page*)

Table 5 (*continued*)

Ref.	Type of composite	Type of Nanomaterial	Fresh Properties Tests		Hardened Properties Tests			Durability Properties Tests	Micro structure Properties Tests	Major Findings
			W	S	CS	SPT	FS			
										stages, except for weak peaks observed in the control and mixtures containing 0.09% MWCNT.
[71]	GGBFS and Metakaolin	NT			✓				✓	The optimum 0.5% NT gives the best results (CS by 72%). The optimum dosage is 1% NT for self-cleaning purposes in this work.
[72]	Metakaolin	NS		✓	✓			✓	✓	NS dosages (0.5–2%). 0.5% NS enhanced CS from 58.3 MPa to 71.1 MPa. SEM: The structure becomes denser and compact (at 0.5%).
[73]	Fly Ash	NS, NT	✓		✓				✓	The addition of 2% NS and NT gained 17.38% and 10.49% in strengths.
[74]	Fly Ash	NS	✓		✓				✓	NS at 20 and 120 min of sonication improvement: CS 3.88%, 13.59%, and Elastic modulus 5.18 %29.93%, respectively.
[75]	Metakaolin	CNT	✓		✓		✓	✓	✓	CNT optimum 0.1% wt. increased Young's modulus, CS and FS by3.8%, 13.2% and 28.7% respectively.
[76]	Fly Ash with Rice Husk Ash	NS, NA						✓	✓	2% NS and 1% NA reduced water absorption. The study concluded that amorphous nano silica particles accelerate geopolymer reactions, resulting in a denser matrix with reduced water absorption.
[77]	Fly Ash	NS, NA		✓	✓		✓		✓	Dosages: 0%, 1%, 2%, and 3% by weight. Optimum: 1–2% increased CS (45%), FS (32%), and elastic modulus (38%).
[78]	Fly Ash	NT			✓			✓	✓	Dosages: 0, 1, 2, 3, 4 and 5% by wt. Optimum: 5%. Increased the surface's resistance to algae and fungi formations
[79]	GGBFS	NS			✓			✓	✓	Dosages: 0.0%, 0.5%, 1.0%, 2.0% and 3.0%. Optimum: 2% increased CS early stage and late stage by 64.15% and 18.24%, respectively.
[80]	Fly Ash	NZn			✓				✓	Nano ZnO Dosages: 0, 2.5, 5.0, 7.5 and 10 wt%. CS decreased (2.5–7.5 %wt.) and slightly increased (at 10% wt.)
[81]	Metakaolin	Nano sand			✓			✓	✓	Nano sand dosages: 2.5, 5, 7.5 % wt. Optimum: 2.5% increased CS to 60 MPa from 36 MPa.
[82]	Metakaolin	NZn			✓			✓	✓	Dosages: 0.3%, 0.5% and 0.7%. The optimum 0.5% increased CS from 30 to 38 MPa. Also, weight loss decreased, as evidenced by TGA.
[83]	Metakaolin	NS		✓	✓			✓	✓	Optimum 5% NS showed higher CS at 8 20 °C and 80 °C. XRD: Quartz dominant, SEM: dense microstructure at 5% NS.
[84]	Rice Husk	GN			✓			✓	✓	GN dosages: 0%, 2%, and 4% wt. and molded in a 5x5x5 cm^3. Optimum 4% GNs increased CS from 13.8 to 17.4 MPa. SEM: denser structure from granular, XRD: crystal diameter of 60.52 nm.
[85]	Natural pozzolan	Graphene				✓			✓	The review study found the optimal dosage of 0.06 % wt, strengthening the CS.
[86]	Natural pozzolan	GO			✓	✓		✓	✓	Graphene oxide improved CS and SPT's mechanical properties by 110% and 52% at 7 and 28 days, respectively.
[87]	Fly Ash	CF			✓		✓		✓	Mineral-impregnated carbon fiber showed promising results, having distribution over the cross-section, densest microstructure.
[88]	Fiber	GNP			✓	✓	✓		✓	Dosages: 0.1%, 0.5% and 1.0%. The optimum 0.5% GNP showed the best enhancement effect on the SPT (69%) and FS (326.1%).
[89]	Fly Ash	NC, NT			✓	✓			✓	Optimal % = NC: 1%, NT: 1.25% by wt. FA. CS (55%), SPT (50%), and density (2.3–3.6%) increased. SEM revealed a denser structure.
[90]	Metakaolin	NS			✓			✓	✓	The optimal 5% NS improved physio-mechanical properties and microstructure, even after exposure to high temperatures (700 °C)
[91]	Fiber	MWCNT	✓			✓			✓	Ultimate stress, strain, and strain energy density increased by 5.67%, 155.78%, and 151.14%, respectively, at 0.15% MWCNT, 2.5% PVA, and 1.0% steel fiber. SEM revealed a denser structure with fewer cracks.
[92]	Natural Pozzolan	NA			✓				✓	An optimal NA dosage of 5% improved overall properties with CS by 34.5%.
[93]	Fly Ash and GGBS	NS with fibers	✓		✓	✓	✓	✓	✓	Optimal 2 %NS, 2 %PP fiber, and 2 %PVA. Increased CS by 4.75%, 13.59%, and 27.14%, respectively. After 30 heat cycles, CS was reduced by 20.26% (PP). It is concluded that PP fibers were weak compared to NS and PVA.

(*continued on next page*)

Table 5 (*continued*)

Ref.	Type of composite	Type of Nanomaterial	Fresh Properties Tests		Hardened Properties Tests			Durability Properties Tests	Micro structure Properties Tests	Major Findings
			W	S	CS	SPT	FS			
[94]	Metakaolin	GO			✓			✓	✓	Microstructure (SEM, XRD, FTIR) results indicate that methanol aids in the stable dispersion of graphene oxide (GO) in an alkaline environment. Also increased CS by 25%.
[95]	Fly Ash	MWCNT with fiber						✓	✓	Dosages = MWCNT: 0.05%, 0.10% and 0.15%, PVA: 1.50%, 2.00% and 2.5%. Optimal = 0.10% MWCNTs and 2.00% PVA resist 175 freeze–thaw cycles.
[96]	Natural Pozzolan	CNT with fiber			✓	✓		✓	✓	CNTs and Basalt fibers increased the CS and SPT by 32.2% and 43.7%, respectively. SEM: CNTs voids filled and dense, cohesive structure.
[97]	Fly Ash with slag	PDMS			✓			✓	✓	The contact angle of GPC increased from 57.32° to 127.64°, reduced water absorption (from 6.96% to 1.61%), and imparting hydrophobic properties to the geopolymers (Optimal PDMS: 5%)
[98]	Slag	PDMS			✓	✓		✓	✓	Optimal PDMS: 4% increased CS (32%), reduced SPT (12.3%), and water absorption (15.8%)

W = Workability, S = Setting time, CS = Compressive Strength, SPT = Split Tensile Strength, FS = Flexural Strength.

Table 6
Thin Films and their Applications.

Types of Thin Films	Applications
1. Aluminosilicate Geopolymer Films are derived from aluminosilicate-based geopolymer materials from precursors like metakaolin or fly ash. These films offer excellent mechanical strength, chemical resistance, and thermal stability. 2. Silica-based geopolymer Films comprise silica-based geopolymer materials from precursors like rice husk ash or silica fume. These films exhibit high-temperature stability, good adhesion, and barrier properties. 3. Hybrid Geopolymer Films combine geopolymer materials with polymers or nanoparticles to enhance specific properties. Polymer components improve flexibility, while nanoparticles enhance mechanical strength or electrical conductivity. 4. Organic-inorganic geopolymer Films incorporate organic compounds, such as polymers or additives, into the geopolymer matrix. These films provide unique properties like enhanced flexibility, improved adhesion, or tailored surface functionalities.	1. **Protective Coatings:** Geopolymer thin films are used as protective coatings for metals, concrete, and glass surfaces, providing corrosion resistance and enhanced durability. 2. **Electronic Devices:** Geopolymer thin films serve as dielectric or insulating layers in electronic devices, offering excellent electrical properties for microelectronics applications. 3. **Environmental Remediation:** Geopolymer thin films act as barrier layers, preventing the leaching of contaminants from waste materials or polluted sites and aiding in environmental remediation efforts. 4. **Energy Storage:** Geopolymer thin films contribute to energy storage systems, serving as electrode materials or separator layers in supercapacitors or batteries.

offering valuable insights into morphological changes over time. Microstructural analyses, particularly involving Nano Silica incorporation, have revealed the formation of supplementary sodium aluminosilicate hydrate gels, enhancing microstructure density. The optimal NS concentration for achieving a uniform microstructure has been determined, shedding light on the pivotal role of chemical interactions between Silica, Aluminum, and alkaline solutions. Furthermore, the addition of PDMS has been scrutinized, revealing its potential impact on pore formation and compressive strength. Field Emission Scanning Electron Microscopy has corroborated the microstructural improvements in geopolymer mortar composites employing diverse nanomaterials. The incorporation of graphene nanosheets has been assessed using SEM, demonstrating their ability to densify geopolymer mortar structures, particularly under elevated curing temperatures. These advanced techniques collectively advance our understanding of nanomaterial-geopolymer interactions, informing the optimization of geopolymer composites for diverse applications in Civil and Materials Engineering.

3.1.1.2. X-ray diffraction (XRD). Researchers can utilize X-ray Diffraction (XRD), an electronic technology, to analyze the elemental compositions of the geopolymer specimen components after the polymerization process. Additionally, XRD enables the determination of the chemical compositions of the raw source binder materials employed in creating geopolymer composites. The authors examined the geopolymer composite specimens' elemental compositions in this section.

Adak et al. [24] examined the structural working of concrete made with an FA-based geopolymer and NS added at a 6 % concentration. They performed XRD testing on their samples, as shown in Fig. 7. The presence of minerals like quartz, etc., was more significant in the NM composite than in the simple mixes. This increase in intensity was linked to the Nano silica (NS) incorporation in the mix, which introduced additional sources of SiO_2 to the mixture. Additionally, they said that in contrast to the reference geopolymer concrete mix, novel phases of quartz (SiO_2), mullite ($3Al_2O_3.2SiO_2$), albite ($NaAlSi_3O_8$), alite (Ca_3SiO_5), kaolinite ($Al_2Si_2O_5(OH)_4$), and calcium $(OH)_2$ crystalline compound were formed in the nano-geopolymer concrete specimens. In the same context of studying the impacts of NS, Behfarnia et al. [27] investigated the effects of micro-NS on the permeability of geopolymer concrete made from GGBFS. The results showed that the control concrete specimens produced three main phases, including calcite ($CaCO_3$), magnesium–aluminum carbonate hydroxide ($Mg_6Al_2CO_3(OH)_{16}{\cdot}4H_2O$), and C-A-S-H gel. In contrast, adding NS resulted in additional phases, including calcium silicate carbonate.

Mustakim et al. [26] also conducted an experimental analysis to show the impacts of adding nano- and micro-silica to geopolymer composite-based fly ash and GGBFS on their fresh, mechanical, and microstructural characteristics. To identify the appropriate NS dose, they performed XRD tests on samples of geopolymer concrete. XRD shows promising results, and that quartz mineral has a peak showing its dominance in nano and micro silica. Additionally, Nuaklong et al. investigated how RHA and NS additives affected the mechanical properties and fire resistance of recycled aggregate high-calcium fly ash-based geopolymer composites [28].

In a recent study, Wulandari et al. [84] explored the use of graphene nanosheets (GNs) in rice husk-based geopolymer composites and examined their morphological properties. X-ray diffraction (XRD) analysis revealed changes in the composition at different concentrations

Table 7
Major findings from the research articles regarding Geopolymer Thin Films and their applications.

Ref	Type of Thin film	Hardened Properties		Characterization Techniques				Durability Properties	Application	Major Findings
		C	Other	SEM	XRD	FTIR	Others			
[117]	Aluminosilicate			✓			✓	✓	Electronic devices (Photovoltaic facade systems)	H_2O/Na_2O ratio of 22.80 and H_2O/Geopolymer (GP) binder ratio of 0.64 were used to prepare a mullite-based precursor for thin film applications in photovoltaic façade systems.
[78]	Aluminosilicate	✓						✓	Protective Coatings	NS/NH ratio: 0.67. Nano TiO_2 (NT) dosage: 0, 1, 2, 3, 4 and 5%. 5 %wt. NT reduced the algae and fungi formations to 54 and 24%, respectively, and served as a protective coating. However, 0.5% is optimum for CS.
[118]	Organic-Inorganic	✓	✓	✓		✓		✓	Protective Coatings	Inorganic: Geopolymer, Organic polymers: polyacrylate, polytetrafluorethylene, and polyurethane. Good tensile strength of 0.15–0.30 MPa. Stable up to 200 °C acting as fire retarding coating.
[119]	Hybrid organic–inorganic	✓		✓		✓		✓	Protective Coatings	Organic, inorganic composite through a synthetic approach based. Melamine resin: 15% increases CS by 40%. Nonflammable under 50 kW/m2 irradiance levels, attractive for thermo-resistant and thermo-insulating panels.
[116]	Aluminosilicate	✓		✓	✓	✓			Protective Coatings	75% FA + 25% as a support for Nano TiO_2 film coating via sol–gel process. Average size of formed anatase phase: 100 nm.
[120]	Aluminosilicate			✓	✓		✓		Energy Storage	Nano TiO_2 film coating via sol–gel dip coating process results in serious cracking. However, the Incorporation of 6% PVP of precursor sol mitigated the cracking, and the resulting TiO_2 film exhibited mesoporous morphology ($\sim$100 nm).
[115]	Aluminosilicate		✓				✓		Protective Coatings	Optimum: Thin film transistor liquid crystal display waste glass (TLWG): 0%, S/N ratio: 2.0 shows highest FS = 10.4 MPa. TLWG > 0% showed promising results in reducing wt. Loss under 230 to 750 °C. Thus, MKGB, with 0–10% TLWG and an S/N ratio of 2.0, can partially replace metakaolin in geopolymer materials.
[121]	Silica Based			✓			✓	✓	Protective Coatings	A thin film of decanoic/palmitic (1:1, wt.%) enhances flame retardant efficiency (FPI: 0.14 to 0.58 $s\cdot m^2\cdot kW^{-1}$; FGI: 1.97 to 0.71 $kW\cdot m^{-2}\cdot s^{-1}$)
[114]	Aluminosilicate		✓	✓	✓			✓	Self-cleaning	Nano TiO_2: 0.5% and 1.0% can be applied by spray as self-cleaning materials.
[122]	Aluminosilicate			✓			✓		Protective Coatings	MK-based GP - brush-applied coatings. Thickness: 1.5 to 11 µm. These coatings can influence the resulting thermal expansion (up to 400 °C)
[123]	Aluminosilicate			✓	✓	✓	✓	✓	Protective Coatings	MK-based GP - Waterborne epoxy resin (WR) at 10%, 20%, and 30%. Optimum: 30% WR as evidenced by microstructure properties.
[124]	Hybrid	✓	✓	✓	✓		✓		Protective Coatings	Hybrid: FA, GGBFS, and MK combined. The optimized mortar achieved CS and FS of 5.65 MPa and 1.73 MPa, respectively, demonstrating its potential as an eco-friendly option for both internal and external coatings.
[125]	Graphene			✓	✓	✓	✓	✓	Protective Coatings	Graphene oxide (GO) coating: 0.05%, 0.1%, 0.5%, and 1% of the binder by wt.) Optimal: 0.1% GO coating enhanced 2 times the magnitude of corrosion resistance.
[126]	Aluminosilicate			✓	✓	✓			Protective Coatings	Micro-sized TiO_2 film coating: 5,10,15%. Optimal: 10% showed promising results, preventing early oxidation and bacterial fouling of mild steel structures.
[127]	Hybrid	✓		✓	✓			✓	Protective Coatings	Hybrid: MK and FA. These coatings are suggested to protect structures exposed to marine environments.
[113]	Hybrid			✓	✓		✓		Electronic Devices	The thin film by spin coating method - heavy oil fly ash doped-calcium carbonate ($CaCO_3$): 0, 1, 2, 3, 4, and 5 wt%. Thickness: 200 nm. Suggested thin films for Optoelectronics.
[128]	Aluminosilicate			✓	✓		✓		Electronic devices (Photovoltaic facade systems)	The process included shifting from a relatively porous bulk to a thin-film configuration suitable for photovoltaic applications (Solar cells).
[129]	Aluminosilicate	✓			✓			✓	Protective Coatings	FA-based thin coating. Thickness: 1 mm showed no cracks regardless of age; 3 mm showed cracks.
[130]	Aluminosilicate	✓		✓	✓				Protective Coatings	FA-based thin coating showed promising results in enhancing CS (15%).

(*continued on next page*)