



Recent developments on natural fiber concrete: A review of properties, sustainability, applications, barriers, and opportunities

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ABSTRACT

To reduce the carbon footprint of traditional concrete materials, natural fiber concrete is vital. This study systematically analyzed 196 peer-reviewed papers using the literature review method to understand fresh properties, mechanical properties, durability, thermal conductivity, sound absorption properties, sustainability, applications, barriers, and opportunities for natural fiber concrete. The findings indicate that natural fiber reduces the concrete cracking rate, increasing tensile strength. Although fibers enhance stress distribution within the concrete, increasing its stability, they reduce compressive strength. Additionally, 85.7% of natural fiber concretes exhibit considerable environmental benefits; however, 28.6% and 43% of the reviewed studies indicate effective economic and social sustainability, respectively. Moreover, this review demonstrates the following potential utilization: 60% in road pavements and 30% in residential buildings. However, natural fiber concrete is still predominantly utilized in the laboratory stage. The following perspective is noteworthy: this review summarizes the barriers that impede natural fiber concrete application and develops relevant recommendations.

1. Introduction

The global population is gradually increasing, and the economy is continually developing. Consequently, the planet's finite resources are being consumed, and large amounts of harmful gases are being emitted; thus, environmental pollution and a scarcity of resources are prevalent worldwide. Especially after the Paris Agreement, which aims to limit the increase in global average temperature to less than 2 °C compared with the pre-industrial period, and to limit the temperature increase to less than 1.5 °C, the state of the environment has become an immensely crucial issue for all sectors of the society (Chen et al., 2022, 2023b). The increase in the amount of greenhouse gases, which adversely affect the natural environment, leads to a rise in global temperatures; consequently, this phenomenon initiates a series of environmental crises such as melting arctic glaciers, reduction of species, increase in natural disasters, mountain fires, and biological extinction (Chen et al., 2023a; Yang et al., 2022a, 2022b). However, the construction industry is

considerably reliant on the extraction and utilization of natural resources; due to the production and transportation of materials to the construction site, construction materials consume considerable amounts of non-renewable resources, and they emit considerable amounts of carbon dioxide (Farghali et al., 2023; Kajaste and Hurme, 2016). Concrete materials, in particular, are widely utilized in construction projects, and they are the most utilized structural building material worldwide (Griffiths et al., 2023).

Concrete is the most basic construction material, and it is essential for housing, infrastructure, and transport projects; compared with other construction materials, it is easy to pour and cost efficient, and it exhibits effective mechanical properties (Achal et al., 2011; Arunachalam et al., 2023); however, some studies indicate that concrete production consumes 0.95 MJ/kg of energy and releases 0.35 kg C/kg of carbon dioxide (Abdalla et al., 2021; Sangadji, 2017). Additionally, concrete is mainly composed of cement; however, one ton of cement clinker emits 0.98 tons of carbon dioxide, and the cement industry produces

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approximately 7% of the carbon dioxide that is released into the atmosphere (Fantilli et al., 2019; Kapur et al., 2009; Qian et al., 2018). Therefore, to reduce the negative environmental impacts of the materials that are utilized in construction projects, researchers have conducted a series of studies and developed measures, such as the utilization of alternative raw materials (Bumanis et al., 2022; Colli-vignarelli et al., 2021; S.S.K K et al., 2020; Sinyoung et al., 2022), waste recycling (Ahmad et al., 2022c; Sithole et al., 2022; Yıldırım and Özturan, 2021), local materials (Morel et al., 2001), and natural fiber concrete (Hesami et al., 2014; Koushkbaghi et al., 2019; Torkaman et al., 2014; Yuzer et al., 2013).

For environmental sustainability, utilizing natural fiber concrete can effectively decrease the negative environmental impact of construction materials (Mei et al., 2022; Osman et al., 2022; Shimamoto and Suzuki, 2019); thus, it is highly sustainable. Farmers and industries usually utilize corn straw, wheat straw, rice hulls, flax straw, and bamboo waste as agricultural waste; to dispose these waste materials, they usually burn them, which leads to environmental pollution and resource wastage (Abdur Rahman et al., 2023; Phiri et al., 2023). If these materials are utilized in construction, a double environmental benefit can be achieved (Liu et al., 2022b; Thomas, 2018). To reduce the amount of concrete that is utilized in construction, natural fiber concrete is utilized. Its production entails applying natural fibers as an admixture, which limits the consumption of natural resources, and utilizing agricultural waste; thus, it indirectly lowers the amount of greenhouse gas that is emitted by municipalities (Chen et al., 2018). Natural fiber concrete is an easy-to-use, simple-to-produce, easy-to-construct, low-cost, and novel building material that offers a novel method of utilizing agricultural waste. Additionally, natural fibers can enhance the force performance of concrete blocks, and they exhibit economic and environmental benefits (Amin et al., 2022; B., S. et al., 2023).

As one of the highly environment-friendly and sustainable building materials in the construction sector, the mechanical properties of natural fibers have become a key element for researchers to assess the suitability of the materials (Elfaleh et al., 2023; Imraan et al., 2023; Maithil et al., 2023). The finding that the tensile strength of natural fiber concrete effects a key role in enhancing the cracking resistance of concrete, which was significantly increased by adding specific types of natural fibers, emphasizes the importance of improved mechanical properties for the application of natural fiber concrete (Farooqi and Ali, 2023; Hamada et al., 2023). To comprehensively assess the mechanical properties of natural fibers, natural fiber concrete was compared with conventional concrete; furthermore, the study highlighted the performance of natural fiber concrete in regard to compressive strength and durability and highlighted its potential use in different applications (Alomayri and Ali, 2023; Martinelli et al., 2023). In addition, due to the presence of advanced chemical hydroxyl fibers in natural fibers, blending with geopolymer composites leads to poor moisture absorption, stability, and low fire resistance; therefore, researchers have utilized hybrid fibers to overcome the limitations of natural fibers (Moujoud et al., 2023). By adding natural fibers to geopolymer composites, both the durability and mechanical properties of concrete can be enhanced (Dhasmana and Singh, 2023). The hybridization of coconut husk fibers with polyvinyl alcohol (PVA) fibers enhanced the impact resistance properties of geopolymer concrete media by 60% and exhibited ductile deformation patterns; the thermal conductivity of bagasse fibers was significantly lower than that of other geopolymer binders, leading to more optimal thermal insulation within the geopolymer composites (Rajendran et al., 2023).

With the increasing global focus on sustainable and environmentally friendly solutions, research on all aspects of mechanical properties, sustainability, and other aspects of natural fiber concrete materials has effected significant progress in development and innovation, but also in its complexity and diversity. Owing to the diversity of natural fiber concrete research, the comprehensive review of the existing literature is urgent and imperative; thus, the gaps in the existing literature research

can be filled, and the study can ensure that it reliably reflects the latest advances in natural fiber concrete in the field of sustainable building materials. However, the different types of natural fiber concrete are highly variable. Therefore, this study systematically analyses the mechanical properties, sustainability, applications, obstacles, and future opportunities pertaining to current mainstream natural fiber concrete materials using the literature review method. This review paper analyzes the mechanical properties of corn fiber concrete, wheat fiber concrete, rice husk fiber concrete, flax straw fiber concrete, and bamboo fiber concrete. Additionally, this review explores the environmental, economic, and social sustainability of the aforementioned natural fiber materials. Moreover, it demonstrates the application of natural fiber concrete in the construction industry, and it examines the obstacles and opportunities for further research. Finally, it provides relevant and up-to-date information on natural fiber concrete that can be utilized to develop green buildings and to decrease the amount of non-renewable building materials. This paper is structured as follows: Section 2 describes the review methodology; Section 3 offers the natural fiber concrete properties; Section 4 provides an analysis of the sustainability of natural fiber concrete; Section 5 demonstrates natural fiber concrete applications, barriers, and opportunities; and Section 6 presents the conclusion.

2. Research methodology

To accurately review the current barriers, progress, and future research directions for natural fiber concrete, the research process was divided into five main steps (Fig. 1). First, Web of Science (WoS) and Google Scholar were selected as the primary database for this review paper; subsequently, we initially input the first six keywords of the research topic to obtain over 1000 pieces of literature. Based on the proposed research topic, the abstracts and full texts of the literature were read, and 196 pieces of literature were finally identified. Based on the selected literature, the content was analyzed; thus, the study derived the mechanical properties, sustainability, applications, barriers, and opportunities of natural fiber concrete.

This review paper examined the literature related to the field of natural fiber concrete with data obtained from the WoS Core Collection database, which contains over 10,000 disciplines and is fairly authoritative and comprehensive (Cavacini, 2015). Although Google Scholar exhibits a broader data collection, it has a relatively high duplication rate compared to WoS (Bar-Ilan, 2008). Furthermore, it was observed that there was no significant difference in the analysis results when the two databases were utilized concurrently (Adriaanse L and Rensleigh, 2013). Therefore, this review paper utilizes WoS as a valid database for the review study.

Research in the field of natural fiber concrete is extensive, and the number of keywords utilized in the literature search was enormous. Therefore, the number of studies retrieved was also quite high. Based on the research topic herein, six keywords were utilized: corn fiber concrete, wheat fiber concrete, rice husk fiber concrete, flax straw fiber concrete, bamboo fiber concrete, and sustainability. Furthermore, the keyword were joined together with the “AND” operator to obtain the maximum results. Based on the keyword search, there were initially 1238 searched papers; the time range was set to 2020–2023 to identify the latest state-of-the-art research in the field of natural fiber concrete. Subsequently, by reading through the abstracts, introductions, and conclusions of the papers, 654 papers with clear conclusions on natural fiber concrete research, closely related to the six keywords and highly relevant to the review topic, were screened. To further ensure that this review represents recent research findings and advanced knowledge on natural fiber concrete, which can ensure the credibility of the research arguments and conclusions, Journal Citation Reports (JCR) Q1 and Q2 papers were screened based on literature journal partitions, and the papers were carefully read. The 196 papers that fit the theme of this review article were retained using Endnote and downloaded by clicking

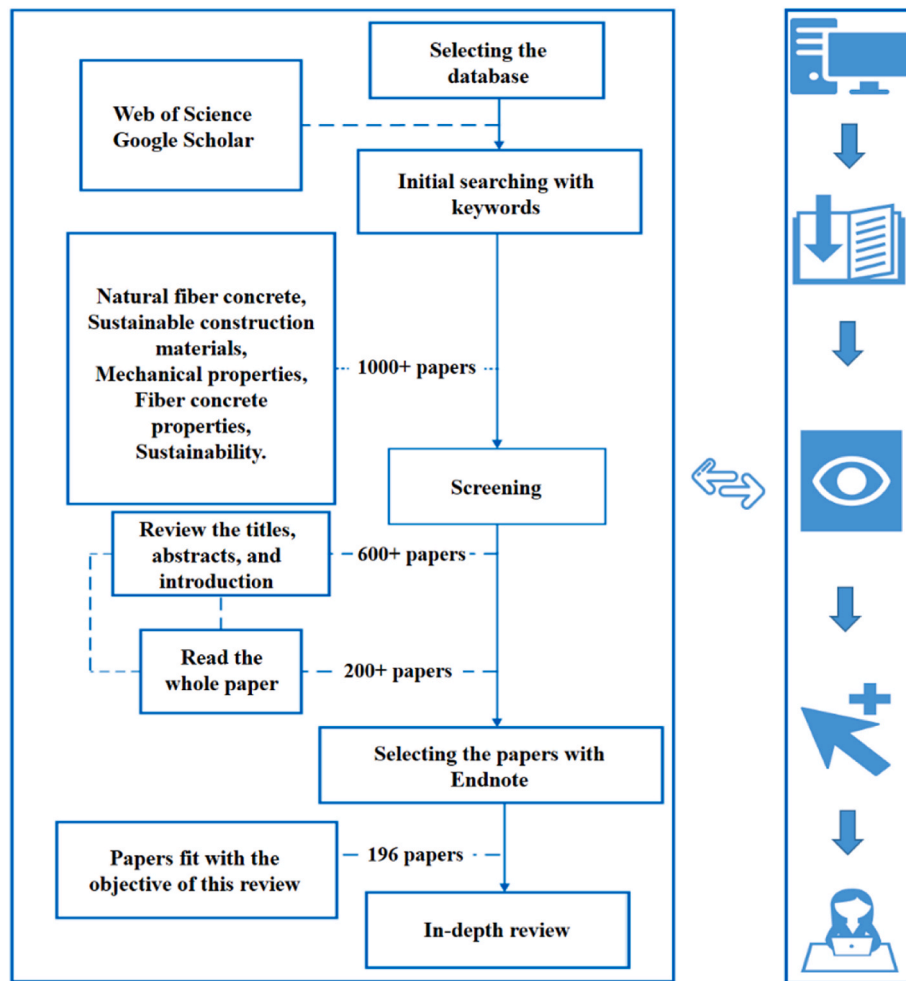


Fig. 1. Research process of this review paper.

on the hyperlinks. Finally, the downloaded papers were read carefully and utilized as references for this review paper.

3. Natural fiber concrete properties

3.1. Fresh properties

On the basis of slump, concrete mixture workability is determined. The novel concrete mixtures and workability were significantly impacted by the quantity and length of flax fibers as well. Page et al. (2017) indicated that concrete with 0.3% 36 mm flax fibers added decreased in slump from 16.5 cm to 5.5 cm compared to concrete with 0.1% 12 mm flax fibers, and the scholar also demonstrated that concrete with long fibers and high fiber content leads to a decrease in the flowability of the mixture. The addition of flax fiber to the concrete mixture increases the void ratio due to the extra, entrained air, thus increasing the amount of entrained air and decreasing the particle density; however, there is a greater probability that the fibers will overlap, which could lead to more air being entrained during mixing (Page et al., 2017). Hamzeh et al. (2013) compared the change in the density of concrete with different rice husk fiber contents added to concrete and observed that increasing the rice husk content from 0% to 5% decreased the density of concrete from 2340 kg/m³ to 2105 kg/m³. More bamboo strands lead to the following scenario: the concrete becomes more cohesive and internally resistant while losing fluidity. More water is required to cover the larger surface area of the coconut fiber, which consumes less free water for oiling and reduces the concrete droop.

Moreover, because the internal friction between the concrete components is increased by the coconut fiber, more cement paste is required to minimize this friction (Ahmad et al., 2020a). In a test that entailed the addition of coconut fiber to concrete, Sivakumaresa Chockalingam and Rymond (2022) discovered that the slump was reduced by 20–35%. With the addition of 2% coconut fiber, a high fresh density was achieved, and as the coconut fiber concentration increased, the fresh density of the concrete decreased. This observation may be rationalized as follows: coconut fiber reinforced concrete exhibits less reinforced concrete for crack prevention, fewer plastic shrinkage voids, and produces denser concrete, which enhances the fresh density of concrete (Ahmad et al., 2021a). By changing the length and proportion of fibers, the slump of coconut fiber-reinforced high-strength concrete was reduced by 87.5%, and the density was reduced by 2.7% compared with that of fiber-free high-strength concrete (Ahmad et al., 2020b). Banana fibers immensely enhanced the slump of concrete (by 1.6 times); according to Jameel et al. (2022), natural banana fibers absorb water, which lowers the water content of the other concrete components and decreases the workability of the mixture when fibers are added. Abrar (2021) tested a 30 mm reduction in the slump of banana fiber concrete, and compared the value to that of conventional concrete. Kesavraman (2017) utilized 0.5%–2% banana fiber incorporated into concrete and observed a reduction in the concrete's workability.

3.2. Mechanical properties

Due to cellulose swelling, which enables polysaccharides to absorb

water from the environment through hydrogen bonding, corn husk fiber concrete becomes lighter than fine aggregates and sand; additionally, cellulose swelling leads to an increase in the size of the fibers, which negatively affects the concrete's longevity (Anggraeni et al., 2022; Jarabo et al., 2013). The cement particles readily adhere to the surface of the maize fibers; thus, by generating an adhesive strength that accelerates repulsion between the maize fibers and the soil–cement particles, they become increasingly resistant to the imposed stress. By contrast, due to the interlocking force that affects the fiber network, cement particles and fibers become immobile when they are subjected to load; thus, the strength of the concrete is enhanced (Duong et al., 2021a). Duong et al. (2021b) observed that the application of corn husk fiber to concrete increases the tensile strength of concrete by 72.6%, which leads to a decrease in the loss of post-peak stress. By contrast, the cellulose polysaccharide that is generated when corn cellulose hydrolyses is sensitive to alkaline corrosion, and this polysaccharide is easily soluble; therefore, due to excess cellulose sugars, the concrete exhibits a decrease in compressive strength, and the cement hydration time increases (Laborel-Préneron et al., 2018; Lei et al., 2020; Niu and Kim, 2022).

Wheat fibers exhibit shallow pores that appear on their surface, which increases their roughness and increases their surface area; thus, in regard to the degree to which wheat fiber binds with concrete, it exhibits a greater adhesion (Geremew et al., 2022). Wheat straw considerably enhances the performance of concrete pavements and that of flexural and shear reinforced concrete; the concrete matrix enhances the rough surface of the straw bridges or seams. When distributed straw is applied to wheat fiber-reinforced concrete, the concrete effectively distributes stress, which delays or prevents the onset of initial cracks and limits the need for steel reinforcement (Farooqi and Ali, 2018a). Due to the distribution of straw within the straw-reinforced concrete specimens, the specimens exhibited considerably slow crack expansion. To achieve bond formation in cement and fiber matrix, Suhail et al. (2022) tested the irregular surface properties of wheat straw fiber concrete that corresponded to a high tensile strength (40 MPa). The stitching and bridging effect that the wheat straw exhibits when it is utilized in concrete can enhance concrete's energy absorption and toughness index; thus, wheat straw can inhibit the formation of microcracks. However, due to poor compaction or improper mixing, the concrete's compressive strength decreases (Farooqi and Ali, 2018b). The decrease in compressive strength may be occasioned by the addition of low-density wheat fibers, which decreases the amount of cement in the mixture and lowers the rate of internal degradation that occurs during external compression loading (Farooqi and Ali, 2022). Moreover, due to the high pH of the pore solution that exists within the concrete, straw contains a large amount of cellulose and hemicellulose; these nutrients leach sugar from straw concrete and penetrate the internal structure of the concrete, which hinders cement hydration; thus, straw concrete exhibits decreased compressive and flexural strength (Ataie, 2018). Moreover, when the tensile strength of the wheat straw concrete is lower than that of the straw, the straw undergoes pull-out.

The silica in the rice husk ash reacts with the cement in the concrete to produce a volcanic ash reaction, and the rice husk ash can enhance the concrete's water absorption by filling the pores and voids in the concrete matrix (Ha et al., 2022). According to Danso (2020), rice husk fiber inhibits the hydration reaction that occurs in the mortar; thus, the cohesiveness between concrete particles is weakened, which results in a decrease in the compressive strength of rice husk fiber concrete. When the concrete is subjected to external loading, cracks begin to form, and the rice hull fibers prevent the cracks from expanding. The volcanic ash effect of rice hulls leads to a well-bonded excessive interface between concrete and mortar, and the presence of the fibers absorbs some of the stresses and prevents the cracks from expanding rapidly, which further increases the ultimate tensile stress of the concrete (Liu et al., 2022a). Meanwhile, the shape and length of rice husk fibers can induce a more uniform distribution of forces in the concrete structure and form a fiber

mesh structure; thus, the bridging stresses between cracks during tension and prevent crack development is enhanced (Farhan et al., 2021). However, excessive fibers can disperse the cement colloid in concrete, impede the effective combination of cement particles and fibers, and affect the homogeneity of the concrete; thus, concrete strength and tensile properties decrease (Hakeem et al., 2022). It has been indicated that the most optimal mechanical properties of mortar can be achieved by infiltrating rice husk fibers with a content of 10–20% in concrete, and that the highest compressive strength is achieved when the content of rice husk fibers is 20% (Kannan, 2018; Liu et al., 2022a). In addition, compared with ordinary concrete, the porous structure of rice husk fiber and recycled aggregate bonded mortar absorbs a large amount of water, resulting in the expansion and extension of internal pores and cracks in the concrete; thus, the formation of severe freeze–thaw damage in recycled concrete occurs, and the degree of freeze–thaw damage is positively correlated with the rice husk fiber content (Zhang et al., 2022).

However, the high water absorption that is exhibited by flax fiber facilitates water seepage, which utilizes the pore system; consequently, the concrete exhibits a decrease in strength and rigidity (Huner, 2015). Page et al. (2017) observe that adding 0.3 vol% flax fiber to concrete lowers its compressive strength by 17%, and that it enhances its flexural strength by 21%. An increase in fiber content yields an increase in air porosity. The breakdown of hemicellulose and α -cellulose, which are components of flax fiber, yields a decrease in compressive strength (Netinger Grubeša et al., 2018; Zheng et al., 2015). When flax fiber concrete was tested for compressive strength at 7, 28, and 180 days after curing, Kouta et al. (2020) observed that its high tensile strength effectively enhanced the bonding quality (i.e., adhesion) between the fiber and the concrete matrix, which decreased the stress concentration above the concrete stress concentration zone; thus, the spread of cracks was inhibited, and the mechanical properties of the concrete was enhanced, which further enhanced the compressive strength (Laborel-Préneron et al., 2016). Flax fiber enhances the consistency of concrete and increases its surface area, which enhances robustness and negatively affects workability (Page et al., 2017). The increase in fiber volume fraction and fiber length yield enhanced robustness (Khelifi et al., 2016; Perrot et al., 2013; Wang et al., 2022). Because the flax fibers exhibits high tensile strength, the applied load can be increased; this behavior indicates the inelastic and nonlinear macroscopic characteristic of flax fiber up to the maximum load. The adhesion of the flax fibers to the cement matrix is crucial for preventing brittleness or fracture. Additionally, the gradual load reduction that characterizes the post-peak behavior that occurs after matrix cracking correlates with a progressive macroscopic fracture that affects the fibers (Page et al., 2021). Due to the friction between basic fibers and adjacent fiber cell walls that are located in the fiber bundles, vibration dampening is enhanced (Lai et al., 2019).

Due to its dense and reinforced microstructure, bamboo fiber exhibits satisfactory and stable mechanical properties, which characterize mixed concrete (Li et al., 2021). By bridging any cracks that may form and by allowing the load to be transmitted through the crack edges, the crack-bridging ability that characterizes bamboo fiber can prevent the sudden rupture of the concrete member, which affects its cross-section (Bittner and Oettel, 2022). However, bamboo fibers decrease the concrete's compressive strength. Yusra et al. (2020) added 0.5%–1.5% of bamboo fibers, and the compressive strength of concrete was reduced by 8.2%. However, as the fiber content increases, flexural strength decreases (Bashir et al., 2018). Because bamboo fibers can absorb a considerable amount of water, during the curing phase, concrete may develop microscopic or even large cracks; this cracking may be occasioned by the dimensional changes that are a consequence of water absorption (Ramesh et al., 2021). Alkali-treated bamboo fibers exhibit effective shear and tensile strength as well as enhanced adhesion to the bonding substrate (Costa Junior et al., 2015). The length of the crack that appears in the concrete decreases, and the concrete's ability to

withstand post-cracking loads is enhanced; thus, the cracks exhibit a decrease in their rate of growth, and the ability of the bamboo fibers to withstand such loads is enhanced (Amin et al., 2021). To enhance the mechanical properties of self-compacting concrete, Ede et al. (2019) utilized bamboo fibers. This organic fiber facilitates the production of sustainable concrete, which exhibits a longer life cycle, enhanced fracture resistance, and lower maintenance costs. According to Sheng et al. (2019), the utilization of bamboo fibers could increase the resistance to rutting and low-temperature cracking of asphalt concrete. Furthermore, when bamboo fibers are heated, hemicellulose break down occurs; consequently, irregular gaps that allow the asphalt binder to be absorbed are formed. Thus, the effectiveness with which the bamboo fibers adhere to the asphalt binder is potentially impacted.

The concrete with 1.5% coconut fibers exhibited 25% higher compressive capacity and 3% higher flexural strength than the reference concrete (Ahmad et al., 2020b), and 15% higher compressive strength than the reference concrete after 28 days of curing (Ahmad et al., 2021a). Jamshaid et al. (2022) also observed that the addition of 0.5% coconut fiber to concrete increased the compressive strength by 9%, resulting in a 73.67% increase in the concrete's tensile strength. In addition, coconut fiber reinforced cementitious mortar exhibited considerable enhancement in flexural properties, with the flexural strength of the coconut fiber concrete being 45% higher than that of normal concrete after 28 days of curing with 2% coconut fiber (Ahmad et al., 2021a). By limiting more water absorption during curing through the low water absorption properties of coir fibers, which prevents further pore formation in the sample, the formation of cracks is delayed when compressive loads are applied; thus, the compressive strength is higher (Sivakumaresa Chockalingam and Rymond, 2022). The plant fibers become brittle, and the link between the concrete and the fibers weakens or dissolves over time due to the concrete's alkali action, which lowers the strength of the fiber concrete. Additionally, the creation of air gaps due to improper compaction during specimen casting diminishes compressive strength, whereas an increase in fiber content and length decreases the compatibility of fresh concrete. The ideal percentage of coconut fiber in concrete, according to Rumbayan et al. (2019), was 0.25%, which boosted the material's compressive strength by 19% after 28 days of curing. Additionally, because coconut fibers prevent fracture formation and boost tensile strength, they increase the elasticity and flexibility of concrete. Coconut shell fibers reduced the plastic cracking of cement composites. No plastic cracking was observed in samples with 2.5% and 4% coconut shell volume at water–cement ratios of 0.3 and 0.35, respectively. However, the tensile strength of fiber concrete is affected by the content, and when the fiber content is excessive, the tensile stress decreases (Ahmad et al., 2022a). Coconut fibers prevent crack rupture; thus, they enable cracks to flow around the fibers and transfer stresses, increasing bending capacity by inhibiting fracture development. Ahmad et al. (2022b) determined that coconut fibers were more effective in increasing flexural strength (47%) than compressive strength (12%).

Saad et al. (2022) observed that concrete with the addition of 1–3% banana fiber experienced a drastic reduction in compressive strength after 28 days (6.8%–29.2% decrease). The weak bonding of the banana structure to the high-strength concrete resulted in weakened tensile and flexural strengths of high-level banana fiber concrete. Due to the high fiber content in concrete, the pore volume increases, which indicates that the material's compressive and tensile strengths is negatively affected (Shen et al., 2022). However, Ali et al. (2022) added low volume (0.5%) of banana fibers for more optimal distribution of compressive stresses, effectively increasing the compressive strength of concrete by 5.8%, splitting tensile strength by 40% and flexural tensile strength by 10%. Afraz and Ali (2021) compared the difference in the flexural properties of fiber concrete and plain concrete by preparing banana fibers with a 50 mm fiber length and 5% fiber content as a cement mass ratio. The results indicated that the flexural toughness index of concrete with the addition of banana fibers increases and can effectively enhance

the impact load resistance of concrete. This observation may be rationalized as follows: banana fibers form a structure that is capable of absorbing and dispersing impact energy within the concrete. When an impact occurs, these fibers absorb some of the energy and reduce the impact force, enabling the concrete to absorb energy more optimally and reducing the risk of cracking and damage (Bhaskar et al., 2022). Furthermore, the addition of fibers to concrete reduces the modulus of rupture; however, it enhances the concrete's toughness index due to the favorable energy absorption properties of natural fibers. In addition, the alkalisation of banana fibers with the addition of NaOH increased the tensile strength by 181.5% and the flexural strength by 56.63% (Ernest and Peter, 2022), which further illustrates that the chemical modification of natural fibers enhances the physical and mechanical properties of the materials and widens the scope of application in the domains of the respective materials. In addition, banana fiber enhances the thermal stability of polymeric materials compared to other natural fibers, which broadens its application in the temperature and heat resistance field (Sivaranjana and Arumugaprabu, 2021).

3.3. Durability

The natural fibers in the concrete react with the absorbed water and moisture, which leads to fiber deterioration. Thus, holes and pores develop in the concrete matrix, potentially reducing the concrete's strength. The overall water absorption capacity of natural cellulose fiber reinforced concrete ranges from 4.25% to 9.25% when the fiber additive is changed from 0.5% to 3% (Jamshaid et al., 2022). At smaller banana fiber volumes (0.25% and 0.5%), the pore dispersion within the concrete is more optimal, and the fibers do not increase the porosity (Ali et al., 2022). With respect to its chemical composition, corn husk fiber, which exhibits exceptional strength and robustness comprises 1.9% ash, 22% lignin, 31% hemicellulose, and 43% cellulose. Corn stalks consist of a husk and a core (Luo et al., 2017; Youssef et al., 2015). Corn husk fiber is characterized by high water absorption (4.8 cc/g); thus, it exhibits an increase in lateral and longitudinal dimensions, which yields an 11% increase in the cross-sectional area. The higher the water absorption, the worse the durability, and this relationship may be rationalized as follows: water contains various harmful compounds that can penetrate into the concrete, which leads the concrete to break and occasions reduced durability. Wheat straw fiber exhibits high water absorption due to the large number of hydrophilic hydroxyl polar groups in the cellulose, Jiang et al. (2023) observed that the water absorption of wheat straw fiber concrete attained 149% at 0.5 h. By attaching wheat straw fibers through modified emulsions, these water-resistant modifiers increase the difficulty with which water enters the fibers; the water slowly penetrates, which indirectly enhances the water resistance of the wheat straw fibers (reducing water absorption by 61–135%).

Rice hulls exhibit an excellent pore network, which is crucial for lightweight concrete; compared with ordinary concrete, the resultant lightweight concrete exhibits a uniform distribution of air voids and a low density (Winarno, 2019, 2021). Due to their unique geometry, rice husks particles randomly orient to three dimensions and sizes when concrete is mechanically compacted, thus increasing the bond between the fibers and the concrete by connecting the pores between the two to increase the absorption rate. The particle packing density exhibited a negative correlation with water absorption and the coefficient of determination R^2 was 0.93 (Endale et al., 2023). The utilization of rice husks in concrete yields immense benefits; its application in lightweight concrete decreases the concrete's density and ultrasonic pulse rate. By contrast, as the amount of rice hulls increases, the pore volume that is exhibited by the concrete increases; thus, volatiles are eliminated (Yuzer et al., 2013). Koushkbaghi et al. (2019) tested the expansion coefficients of non-fibrous and fibrous concretes, and the findings indicated that rice husk fiber concrete with 20% admixture content exhibited the lowest diffusion coefficient, which can be rationalized as follows: the large amount of rice husk fibers formed by the calcium silicate gel enhances

the concrete's pore structure and reduces its porosity. In addition, the presence of rice husk fibers increases the concrete's durability against acid attack, which is occasioned by the lower calcium hydroxide content of rice husk fibers; thus, less mass and strength is lost in the decalcification reaction, decreasing the concrete's susceptibility to acid attack (Althoeay et al., 2022).

The flax fiber comprises 10–40 basic bundles of microfibr aggregation, fiber through the capillary pressure of microfibers, a fiber surface that exhibits a rough texture that enhances water absorption, and fiber in the cement matrix hardening process to release water and shrinkage (Rahimi et al., 2022). Flax fibers are porous and hydrophobic, and when exposed to alkali, they can become hydrophilic; thus, they are a potentially effective option for concrete curing (Imanzadeh et al., 2020). To cure the hydrated cement matrix, the addition of water is crucial; this action limits the intensive demand for water that is exhibited by cement particles, which comprise hydrophilic flax fibers (Dai et al., 2019). The cellulose molecules in flax fibers are crystalline in nature, which prevents the cellulose from being subjected to carbonation reactions when the concrete structure is exposed to carbonic acid gases, humid conditions, and oxygen for a long period of time (Hamada et al., 2023). Cellulose with higher crystallinity is more stable and resistant to carbonation. Moreover, the carbonation reaction is affected by humidity conditions; low humidity (0%) flax fibers cannot absorb enough water to support the carbonation reaction of concrete, whereas high humidity conditions (100%) fibers increase the diffusion of carbon dioxide and water, which leads to a higher degree of carbonation for the concrete matrix (Rakhsh Mahpour et al., 2023).

The application of bamboo fibers increases the demand for water in the cement due to the absorption of water by the fiber nodules, and the hydrophilic nature of bamboo fibers promotes the development of internal joint capillaries; thus, the water absorption and apparent voids become larger (Xie et al., 2015). The overall water absorption capacity of natural cellulose fiber reinforced concrete ranges from 4.25% to 9.25% when the fiber additive is changed from 0.5% to 3%. The likelihood that concrete would deteriorate when exposed to foreign, hazardous chemicals such as chloride ions and sulfate ions increases with pore volume (Velandia et al., 2018). The high water absorption rate of fiber-reinforced concrete is demonstrated by the cellulose in plant fibers, which includes several hydrophilic hydroxyl groups. The elastic porous cell walls also increase the swelling capacity of fiber cells following water absorption. Darsana et al. (2016) used coconut fiber instead with up to 10% of cement to prepare roof slabs with 6.25% higher water absorption than ordinary cement concrete slabs. More and Subramanian (2022) utilized 2% coconut fiber incorporated into concrete to enhance water absorption by 0.7%, and the fiber increased the bonding and compactness between the concrete matrix and reduced the porosity by 1.1%; thus, the coconut fiber concrete exhibited reduced chloride ion penetration. After acid and alkali attack, the coconut fiber concrete lost 0.79% of its weight and 6.13% of its compressive strength; thus, it become more susceptible to erosion than conventional concrete. The inherent weak corrosion resistance of natural plant fibers adversely affects the concrete's corrosion resistance. Ramli et al. (2013) conducted tests on the corrosion resistance of coconut shell fiber composite concrete. It was observed that coconut shell fibers enhanced the mortar's microstructure, and that NaCl from seawater crystallized on the fiber surface, increasing the brittleness of the fibers and thus reducing the concrete strength. When exposed to tropical weather, coconut fiber reinforced concrete developed a deeper carbonation level (150% increase), which was indicative of reduced permeability. However, the increased coconut fiber content prevents the cement paste from filling the gaps in the microstructure, increasing the carbonation of the concrete structure. The inclusion of coconut fiber restricts the CO₂ diffusion channels and raises the resistance to CO₂ penetration into the concrete (Ahmad et al., 2022b).

3.4. Thermal conductivity

By incorporating plant fibers, concrete becomes more porous, which improves its air content and enhances its ability to insulate heat (Trabelsi and Kammoun, 2020). Wheat straw concrete exhibits a low thermal conductivity (0.067 W/mK), and this thermal conductivity decreases with increasing cellulose content, which indicates that wheat fibers are excellent thermal insulation materials that can enhance the warmth retention exhibited by the concrete (Binici et al., 2020). Pachla et al. (2021) observed that by adding 15% of 3 cm rice husk fibers, the thermal conductivity of concrete could be reduced by 0.0623 W/mK, thus enhancing the thermal conductivity of porous concrete. Because rice husk exhibits a thermal conductivity of 0.036–0.08 W/mK, rice husk concrete exhibits an immensely low thermal conductivity (0.10–0.13 W/mK) (Chabannes et al., 2014). Yu and Sun (2018) observed that the rice husk fibers that were utilized in insulated wall panels contributed to a reduction in the thermal conductivity of the wall panels from 0.96 W/m·°C to 0.181 W/m·°C, thus attaining the requirements for insulation materials in engineering (thermal conductivity below 0.20 W/m·°C). Yu and Sun (2018) observed that the apparent decrease in the density of concrete and the resultant decrease in thermal conductivity, which are a consequence of the increase in rice husk fiber content, indicate a gradual increase in thermal insulation qualities. However, with respect to rice husk concrete, the typical compressive strength and flexural strength are significantly diminished. Because the presence of rice husk indirectly increases the water vapor diffusion resistance factor, the resultant hollows reduce heat transfer. Additionally, the low thermal conductivity, which prevents the installed reinforcement from heating up, enhances the concrete's high-temperature performance (Yuzer et al., 2013). The surface of the bamboo fiber and that of the absorbent binder becomes rougher after heat treatment, which indicates the high temperature stability that bamboo fiber exhibits when it is utilized in concrete (Li, 2019). However, the hydrophobic asphalt and the hydrophilic bamboo fibers can potentially decrease the interfacial adhesion that occurs between the bamboo fibers and the asphalt substrate (Liu et al., 2014; Yu et al., 2021). Moreover, Asim et al. (2020) observed that the thermal insulation performance of concrete mixed with 10% coconut shell fiber was high compared to that of sugarcane fiber, jute fiber, and sisal fiber concrete.

3.5. Sound absorption properties

Corn cob concrete, which exhibits high cellulose content, is partly derived from corn cob, and it is a porous agent, which decreases the density of concrete. The porous structure of the corn cob fibers is the basis of its acoustic absorption properties, where sound waves are effectively attenuated through the porous structure by multiple reflections, scattering, and absorption within the concrete material (Lahououi et al., 2020). Corn cob concrete exhibits an open fibrous structure compared with conventional concrete (Ibitoye et al., 2023). This microscopic gap between the fibers and the properties of the fiber surface enable it to trap sound waves and induce dissipation of acoustic energy, enhancing the overall acoustic absorption performance of corn-fiber concrete. For sound absorption and higher anechoic performance, high internal porosity and low density are crucial, and they are usually quantified by using the sound absorption coefficient. Oancea et al. (2018) compared the true absorption coefficients of five different sustainable materials based on two concrete samples of 40 mm and 80 mm, and the study indicated that the most optimal material in the 40 mm sample was the corncob concrete, with a 0.193 noise reduction coefficient. Another experiment has similarly verified that corncob concrete can exhibit high sound absorption coefficients in the low and medium frequency ranges, especially in the low frequency range where absorption is significant (Yang et al., 2020). Pachla et al. (2021) observed that all concrete with added straw fibers exhibited a more optimal sound absorption capacity.

In summary, fiber decreases the rate of concrete cracking; furthermore, due to its pore structure and bridging effect with the concrete matrix, it increases the tensile strength. The fibers enhance the stress distribution within the concrete, thus increasing its stability; however, it reduces the concrete's compressive strength. Moreover, the fibers are highly absorbent; thus, their surface area increases, and their adhesion to the substrate is enhanced. Furthermore, an increase in the amount of fibers yields a decrease in the density of the concrete, and the resultant pore structure yields a decrease in the heat transfer of the concrete and acoustic velocity of the internal air; hence, the concrete's thermal and noise reduction properties are enhanced. However, most natural fiber concrete materials are still in the mechanical properties research stage. With respect to the seven types of fiber concrete, Fig. 2 summarizes a variety of fiber concrete, and research on their fresh properties, mechanical properties, and durability can be further enhanced. Table 1 summarizes the performance variation of concrete with optimal fiber proportioning.

4. Sustainability assessment of natural fiber concrete

Sustainability assessment is a valuable tool for measuring the sustainability of a product, which is usually examined from three perspectives: environmental, economic, and social (Kannan, 2018). Furthermore, sustainability assessment of buildings is a complex and multifaceted process (Zhang et al., 2022). The sustainability assessment that is usually utilized for the construction of green buildings entails the adoption of green design, selection of green construction processes, and utilization of sustainable building materials (Huner, 2015). The utilization of natural fiber concrete is a potentially effective method of reducing the greenhouse gas emissions that are emitted by buildings, and it exhibits positive social and economic impacts (Netinger Grubeša et al., 2018). Therefore, Table 2 depicts an assessment and analysis pertaining to the environmental, economic, and social sustainability of various natural fiber concrete materials, and focuses on specific countries.

In various countries worldwide, the construction industry is a leading consumer of energy and materials (Asdrubali et al., 2015; Ding, 2014; Maraveas, 2020). To ensure carbon neutrality and to safeguard the welfare of future generations, researchers are exploring renewable energy and sustainable materials that can be utilized in the aforementioned industry (Chen et al., 2019a; Mistri et al., 2020). Due to the low cost and unsatisfactory environmental sustainability of traditional materials, researchers are exploring alternative construction materials that

are natural, renewable, and cheap (Danso, 2018). As urbanization progresses, these low-cost, environmentally friendly materials potentially become crucial for infrastructure development (He et al., 2021). Therefore, natural fiber concrete, which comprises maize fiber concrete (Ahmad et al., 2021b), wheat fiber concrete (Farooqi and Ali, 2019), rice husk fiber concrete (Tayeh et al., 2021), flax fiber concrete (Kouta et al., 2021), and bamboo fiber concrete (Chin et al., 2020), is an effective alternative to conventional concrete. Natural fiber concrete promotes the utilization of natural resources, and it substitutes the commonly utilized traditional synthetic fibers with materials that exhibit considerable environmental, economic, and social benefits.

However, Table 2 depicts an analysis on natural fiber concrete, which was conducted over the preceding five years, and it presents the following findings. Not all materials are environmentally, economically, and socially sustainable. First, from the analysis on environmental sustainability, we observed that 85.7% of natural fiber concrete materials exhibit a considerable environmental benefit, which often includes a reduction in CO₂ emissions and facilitates the application of agricultural waste resources (Fig. 3). Between 2017 and 2022, researchers that were based in the USA, Italy, Portugal, Pakistan, Slovenia, and India explored natural fiber concrete materials that are environmentally friendly. However, in 2017, a study that was conducted in Belgium demonstrated that flax fiber concrete (a natural fiber) exhibits a significantly negative environmental impact, and that the ecological aspects such as the cultivation of flax require a large amount of fertilizer. Furthermore, flax fiber concrete, which can extend the life of the concrete by limiting cracking, exhibits a significant environmental benefit. Although most natural fiber concrete materials exhibit satisfactory physical properties and environmental benefits, researchers should conduct a detailed investigation into the environmental benefits of flax fiber concrete.

Furthermore, with respect to the analysis herein, which focused on the economic sustainability of natural fiber concrete, we observed that only 28.6% of natural fiber concrete exhibited satisfactory economic performance. The analysis considered studies that were conducted before 2021, and these studies were conducted in Pakistan and India (Fig. 3). Because Pakistan and India are mainly agricultural countries, they produce large amounts of agricultural waste annually (e.g., upwards of 500 metric tons per year in India) (Bhuvaneshwari et al., 2019). In both countries, the disposal of agricultural waste disposal is an immense challenge. Open burning or field dumping, which releases large amounts of greenhouse gases and pollutes the environment, is usually utilized (Kapoor et al., 2020). Therefore, the resourcization of this agricultural waste could increase its economic sustainability.

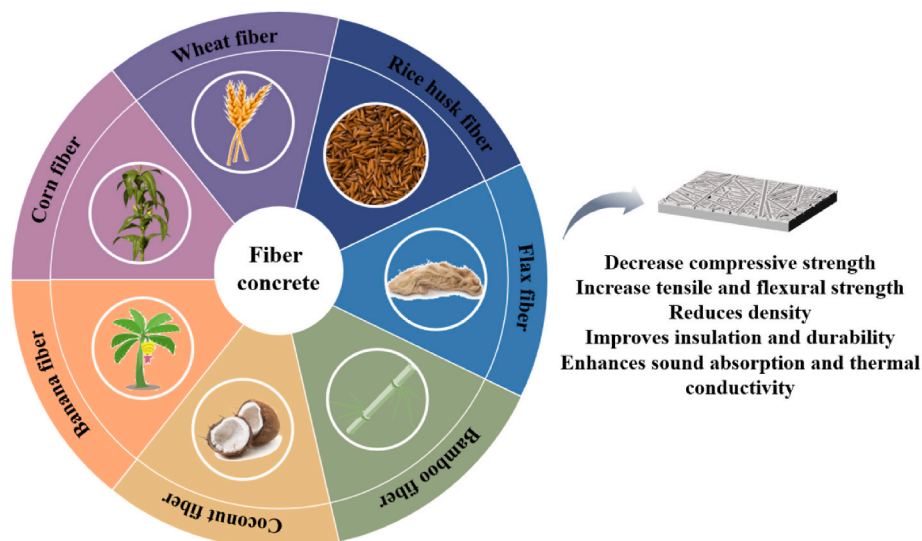


Fig. 2. The effect of multiple fiber applied to concrete.

Table 1

The effect of optimal fiber concrete on concrete properties.

Fiber concrete content	Performance changes	References
0.3% 36 mm flax fiber	60% slump reduction; 65 kg/m ³ density reduction; air entrapment; compressive strength reduction of 5.67 MPa (12.2%); flexural strength enhancement of 0.2 MPa (4%)	Page et al. (2017)
Coconut fiber	Decrease in collapse by 24.69%; increase in compressive strength by 1%; increase in tensile strength by 1 MPa (18%); increase in flexural strength by 1 MPa (16.1%)	Sivakumaresa Chockalingam and Rymond (2022)
1% corn fiber, 2% cement	Compressive strength increased by 35.3%; tensile strength increased by 72.6%	Duong et al. (2021b)
0.6% 50 mm flax fiber	Slump decreased by 1.5 mm; air content increased by 0.8%; compressive strength increased by 0.5 MPa	Kouta et al. (2020)
0.5% bamboo fiber	Compressive strength decreased by 2.64 MPa (4.2%); tensile strength increased by 0.97 MPa (23.4%)	Yusra et al. (2020)
1.5% 50 mm coconut fiber	Decrease in collapse 87.5%; decrease in density 2.7%; increase in compressive strength 25%; increase in tensile strength 20.4%; increase in flexural strength 3%	Ahmad et al. (2020b)
2% coconut fiber	Compressive strength enhanced by 73.3%; tensile strength enhanced by 73.6%; flexural strength enhanced by 50%	Jamshaid et al. (2022)
0.25% coconut fiber	19% increase in compressive strength and flexural strength	Rumbayan et al. (2019)
3% banana fiber	29.2% reduction in compressive strength	Saad et al. (2022)
0.5% banana fiber	Compressive strength increased by 5.8%; tensile strength increased by 40%; flexural strength increased by 10%	Ali et al. (2022)
2.0% coconut fiber	Compressive strength enhanced by 6.4 MPa (15.92%); tensile strength enhanced by 0.34 MPa (7.7%); flexural strength enhanced by 0.72 MPa (15.5%); water absorption enhanced by 0.7%; porosity reduced by 1.1%; adsorption rate increased by 0.002 mm/t ^{0.5} ; chloride ion permeability increased by 14 coulombs; acid and alkali corrosion resistance weakened by 0.37%; resistance to Sulfate erosion increased by 0.36%	More and Subramanian (2022)

However, in 2018, US-based researchers observed that a double-layered façade system comprising green hybrid fiber-reinforced concrete exhibits a higher cost and embedded energy that should be recovered within the first two years and within the initial 8.2 years of operation, respectively. Additionally, as per Table 2, we observed that the studies conducted in Italy, Portugal, Belgium, and Slovenia did not analyze economic sustainability; furthermore, we concluded that natural fiber concrete exhibits a long life cycle and that its cost-effectiveness requires analysis.

Finally, based on the analysis, which is illustrated in Table 2, we observed that 43% of the studies indicated that natural fiber concrete is socially sustainable, and this finding is illustrated in Fig. 3. In regard to the studies that were conducted in the USA, Portugal, and India, the researchers noted that these natural fiber concrete materials exhibit a significant market potential, which is promoted by their environmentally friendly and inexpensive characteristics. However, the study that was conducted in Portugal utilized rice husk ash, which is produced when rice husk fiber is burnt, for concrete production. Because the rice

husk fibers were not directly added to the concrete, the concrete that was utilized in the study cannot be classified as natural fiber concrete. Additionally, in 2017 and 2018, studies that were conducted in two countries, namely Belgium and Slovenia, demonstrated that flax fiber concrete can damage the ecology and soil; thus, this material can negatively affect human health. Moreover, the studies that were conducted in Portugal and Italy did not analyze the social sustainability of natural fiber concrete. Therefore, an investigation on the social sustainability of natural fiber concrete is crucial.

5. Applications, barriers, and opportunities of natural fiber concrete

Amidst the burgeoning emphasis on sustainable construction practices, natural fiber concrete is increasingly recognized as a pivotal alternative, amalgamating ecological sustainability with avant-garde material properties (Madurwar et al., 2013). As it gains prominence in contemporary construction paradigms, a rigorous evaluation of its efficacy across diverse applications becomes paramount. This necessitates a comprehensive examination of its utilization in various realms such as structural, non-structural, energy and insulation, and broader engineering practices. Firstly, natural fiber concrete's rising popularity in structural applications stems from its promise to reduce the concrete cracking rate and improve tensile strength (Ahmad and Zhou, 2022). The integration of natural fibers can enhance stress distribution, making the concrete more resilient to external forces and shocks (Lau et al., 2018). However, it's paramount to note that the introduction of these fibers can also reduce the compressive strength of the concrete (Alam and Al Riyami, 2018). While this might not be an issue in certain applications, it could pose a significant challenge in high-load scenarios where compressive strength is critical. Another area of concern is the long-term durability of natural fibers within the concrete matrix, especially in environments exposed to moisture and biological degradation.

Additionally, for non-structural applications, natural fiber concrete presents a compelling case. Its versatility is evident in decorative items, facades, and non-load bearing elements where the primary requirements often lean towards aesthetics, design flexibility, and limited structural demands (Khan et al., 2020). The use of natural fibers can provide unique textures and finishes, enhancing the visual appeal. Moreover, this type of concrete can be more eco-friendly, especially when sourced from sustainable fibers (Silva et al., 2020). However, the challenge remains in ensuring consistency in finish and performance across batches, as natural fibers can have variability based on sourcing, processing, and integration methods. Finally, the energy and insulation sector stands to gain immensely from natural fiber concrete. Given its inherent properties, natural fiber concrete can offer superior thermal insulation, potentially reducing energy costs in buildings (Florea and Manea, 2019). Its sound absorption properties are also noteworthy, potentially leading to quieter indoor environments. These attributes can contribute to sustainable building practices and enhanced occupant comfort (Asim et al., 2020). Yet, there's a caveat: the long-term behavior of these fibers when exposed to continuous thermal and moisture cycles is not fully understood (Korjenic et al., 2016). Research is needed to ascertain the durability of such concrete mixes over extended periods and under varying environmental conditions.

During the engineering practice, natural fiber concrete is an ideal next-generation construction material that is cheap and lightweight, and it can often be utilized in the construction of houses (Korjenic et al., 2016), roads (Geremew et al., 2021), bridges, and various types of infrastructure (Pandey et al., 2010). Consequently, researchers have initiated a series of studies that explore the effectiveness and economic efficiency of natural fiber concrete materials (Cruz and Fanguiero, 2016; Mohammed et al., 2015; Thiruchitrabalam et al., 2010). Because building materials can effectively contribute to the disposal of agricultural waste and to the conservation of non-renewable natural resources while facilitating the attainment of sustainable development goals, they

Table 2
Sustainability assessment of natural fiber concrete worldwide.

Studies	Countries	Year	Environmental sustainability	Economical sustainability	Social sustainability	Key findings
Hay and Ostertag (2018)	USA	2018	▲	△	▲	The study demonstrated a double faceted system that comprises green hybrid fiber reinforced concrete, which exhibited a 25% decrease in weight and a 9.2% reduction in the annual emission of CO ₂ ; however, the system exhibited a high cost and a high embedded energy, which needed to be recovered within the first two years of operation and within 8.2 years, respectively.
Cappucci et al. (2022)	Italy	2022	▲	N/A	N/A	The researchers conducted a life cycle assessment of fiber concrete blocks that partly comprised wheat husks. They demonstrated that the material is environmentally friendly compared with conventional concrete; however, its economic value and its safety (i.e., its effect on human health and on the ecosystem) has not been analyzed or evaluated.
Marques et al. (2021)	Portugal	2021	▲	N/A	N/A	The study, which utilizes life cycle assessment, demonstrates that rice husk fiber concrete exhibits satisfactory physical properties, and it demonstrates that the material exhibits satisfactory environmental properties. However, the life-cycle costs and social impacts are not considered.
Khan and Ali (2020)	Pakistan	2020	▲	▲	▲	The study analyzed a mixture of six different concrete materials, and it demonstrated that agricultural fiber concrete exhibits satisfactory environmental, economic, and social value. However, the material comprised the ashes of burning rice husks as an additive; thus, it did not entail the direct addition of rice husk fiber.
Van den Heede and De Belie (2017)	Belgium	2017	△	N/A	△	The study demonstrated that due to the extensive use of chemical fertilizers, which are utilized for growing flax, the use of flax fiber concrete adversely impacts the environment and ecological aspects. Flax fiber concrete can extend the concrete's life by limiting cracking; thus, the material exhibits immense environmental benefits.
Merta et al. (2018)	Slovenia	2018	▲	N/A	△	The researchers analyzed flax fiber concrete, and they observed that the material limited CO ₂ emissions; however, they noted that the cultivation of flax is ecologically damaging and that it affects the soil. The researchers also concluded that the durability of flax fiber concrete should be analyzed.
Ramesh et al. (2021)	India	2020	▲	▲	▲	Studies have demonstrated that because bamboo is a low carbon, environmentally friendly, and cheap material, bamboo fiber concrete exhibits economic and environmental benefits, and that it can appeal to a wide market.

Note: ▲ denotes a positive impact, △ denotes a negative impact, and N/A represents not applicable.

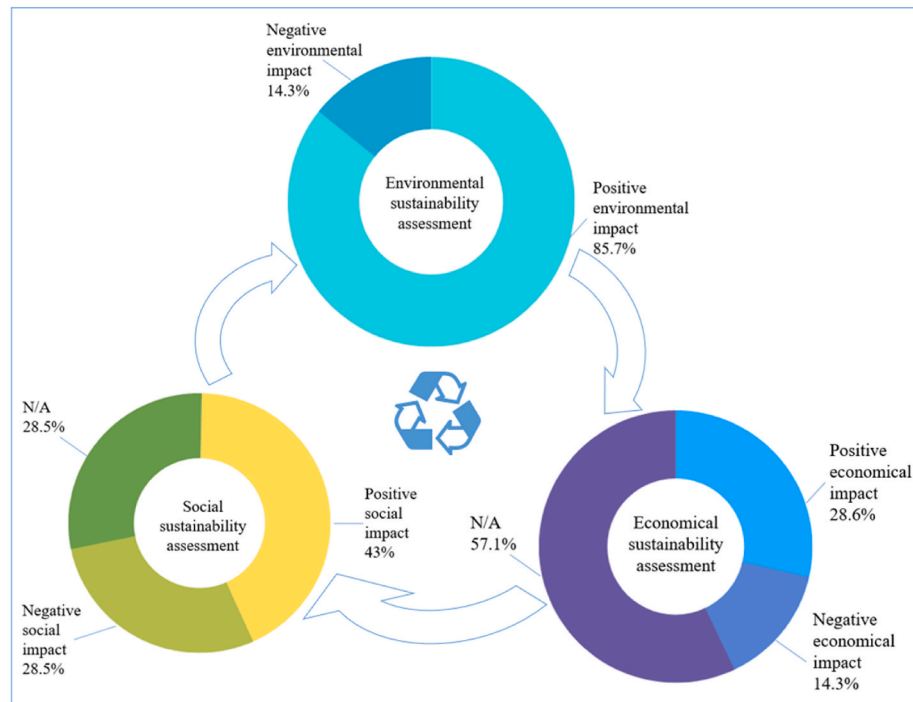


Fig. 3. Sustainability assessment of natural fiber concrete.

promote the development of eco-friendly materials (Chen et al., 2020). Moreover, natural fibers are low-cost, biodegradable, and low-density materials that can limit concrete cracking (Yinh et al., 2021). However, as a component of natural fiber concrete, the utilization of natural fibers exhibits limitations. To address these limitations, their surface and

morphology should be modified, and this modification entails chemical, physical, and biological treatment techniques (Chen et al., 2019b; Khan et al., 2020). The main objective of surface treatment is to promote bonding between the fiber surface and other materials (Geremew et al., 2021). Because its mechanical properties are influenced by parameters

Table 3

Case studies of natural fiber concrete in the building and construction industry.

Project description	Country	Year	Case type	Main content	References
A preparation method for corn stalk fiber material, and its performance investigation in asphalt concrete	China	2019	Road pavement	This study demonstrates that physical methods can be utilized to prepare straw fibers, and it demonstrates that for asphalt pavement applications, chemical methods can be utilized to enhance their standards. However, these optimum preparation processes were conducted under laboratory conditions, and their application in road projects has not been investigated.	Chen et al. (2019b)
Corn stalk from agricultural residue utilized as reinforcement fiber in fiber-cement production	Spain	2013	N/A	This study demonstrates the feasibility of corn fiber concrete. However, to achieve the requisite mechanical and physical properties, which can enhance the performance of the corn fiber concrete, a combination of maize straw fiber and other synthetic fibers as well as a number of chemical processes are necessary.	Jarabo et al. (2013)
A method of manufacturing corn straw cement-based composite and enhancing its physical properties	China	2022	Residential building	This study demonstrates an analysis of the properties of maize straw fiber concrete; the results demonstrate that its insulation properties are satisfactory and that it can be utilized in novel walling materials that are common in rural areas. However, the researchers who are conducting this ongoing study note that maize fiber concrete exhibits immense application potential; however, they are experiencing difficulties in regard to controlling its fiber size.	Niu and Kim (2022)
The contribution of plant fibers in enhancing the behavior and capacity of reinforced concrete that is utilized for structural applications	Pakistan	2018	Road pavement	This study thoroughly analyses load-bearing structure, and it focuses on wheat straw reinforced concrete. The results indicate that it is a potential paving material. However, its durability and performance have not been investigated.	Farooqi and Ali (2018a)
A study on natural fiber reinforced concrete: from its constituent materials to its structural applications	Pakistan	2022	Road pavement	The study analyses the compressive performance, frontal deflection measurements, and crack development of wheat straw reinforced concrete. The study utilized a test section, in which the material was subjected to vehicle loads for 18 months, and it demonstrates that wheat straw reinforced concrete pavements that comprise 1% straw can be utilized in road projects. However, the fatigue, indirect traction, and other parameters that affect this material should be comprehensively investigated prior to actual construction, and a thorough cost analysis should be conducted.	Farooqi and Ali (2022)
An experimental investigation on the mechanical properties of jute fiber reinforced concrete that is subjected to freeze–thaw conditions for pavement applications	Pakistan	2022	Road pavement	The study explored the application of jute fiber reinforced concrete in rigid pavements that are subjected to freeze–thaw conditions; however, the bonding behavior that facilitates the adhesion of the treated jute fibers to the concrete and the long-term durability of the resultant natural fiber concrete should be comprehensively investigated.	Affan and Ali (2022)
The properties of natural fiber concrete materials containing coconut coir and oil palm fibers, and their potential application in residential building projects	Thailand	2015	Residential building	The study analysed natural fiber concrete that is utilized for roof panels and siding that reduce heat transfer in buildings, and the results provided a guideline for the development of fiber cement products that can be utilized in residential buildings. However, the study demonstrates only the utilization of natural fiber concrete as part of the building components; its specific application remains unknown, and researchers are conducting laboratory analysis.	Lertwattanaruk and Suntijitto (2015)
A comparative study on the performance of bamboo fiber and sugarcane bagasse fiber as modifiers in asphalt concrete production	Ethiopia	2022	Road pavement	Studies have demonstrated that when bamboo fiber asphalt concrete is utilized in pavements, it can resist external loads; however, its durability and performance at different temperatures requires further analysis.	Ahmed et al. (2022)
The effective utilization of natural fibers (coir and jute) for sustainable low-volume rural road construction: A critical review	India	2022	Road pavement	The study systematically analyses the utilization of fiber concrete in rural roads; however, its durability and application with respect to motorways and urban roads requires further analysis.	Kumar et al. (2022)
The behavior of oil palm broom fibers that are utilized in reinforced concrete	United Kingdom	2019	Residential building	This study analyzed the three main mechanical properties of concrete that consists of oil palm broom fiber, a short, discrete fiber that exhibits immense potential as a material that can be utilized to manufacture roof tiles, building blocks, lintel beams, building coverings, and facades; however, the study is still in the laboratory stage.	Momoh and Osofero (2019)

Note: N/A denotes not applicable.

such as fiber content, fiber treatment, and manufacturing processes, natural fiber concrete can be utilized for structural, non-structural, and energy and insulation applications (Venkateshwar Reddy et al., 2021). Therefore, Table 3 summarizes the application cases of natural fiber concrete in construction work.

Based on the statistics and analysis pertaining to the application of natural fiber concrete in engineering, we noted that 60% and 30% of the natural fiber concrete was utilized in road projects and housing construction, respectively; however, for 10% of the projects, we could not infer the type of application, as illustrated in Fig. 4. Based on the analysis of the natural fiber concrete that is utilized in road projects, herein depicted in Table 3, we observed that 50% of the research projects were conducted in Pakistan, which is basically an agricultural country that produces a large amount of agricultural waste; therefore, authorities should promote the recycling and application of agricultural waste (Abdullah et al., 2021). China, Ethiopia, and India produced the rest of the research projects. We considered studies that were conducted between 2018 and 2022, and although these studies demonstrate the potential of natural fiber concrete as a road construction material, most of the studies on natural fiber concrete are still in the laboratory analysis stage.

5.1. Road pavement applications

Based on the analysis depicted in Table 3, the findings indicate that it is essential to note that while natural fiber concrete offers various benefits, it may not be suitable for high-traffic and high-stress road applications. In such scenarios, traditional concrete with steel or synthetic fiber reinforcement may be preferred. Additionally, the choice of natural fiber and mix design should be carefully considered to meet specific project requirements and environmental conditions. Additionally, due to the existence of different road classes, the performance requirements pertaining to natural fiber concrete vary. Therefore, before utilizing natural fiber concrete in road pavement projects, it is crucial to conduct thorough material testing and engineering analysis to ensure that it meets the required performance and safety standards for the specific application. Moreover, local regulations and guidelines should be consulted to ensure compliance with construction standards. In summary, the future application of natural fiber concrete in different pavement projects, such as rural roads, urban roads, and motorways, requires thorough analysis, and its durability in practical projects requires further investigation.

5.2. Residential building applications

Based on the analysis depicted in Table 3, which entails the application of natural fiber concrete in residential buildings, the potential utilization of natural fiber concrete in residential buildings has been analyzed; we analyzed studies that were conducted from 2015 to 2022, and these studies were conducted in Thailand, the UK, and China. The results indicate that natural fiber concrete exhibits considerable insulating properties and that it can only be utilized as part of building components such as roof panels, siding, and facades. Although the application of natural fiber concrete in residential buildings exhibits immense potential, it is a theoretical analysis, and its application in practical engineering requires further investigation. In addition, due to the different types of buildings, the performance requirements of natural fiber concrete vary. Therefore, in regard to its application in rural residential and urban residential buildings, the life cycle of natural fiber concrete requires further evaluation.

5.3. Barriers and opportunities

According to the analysis depicted in Table 3, we observed that in 2013, several researchers from Brazil demonstrated the viability of natural fiber concrete applications; however, they did not demonstrate the various application scenarios. The preparation of natural fiber concrete is highly complex; it entails physical and chemical treatment, which enhance the performance and application requirements of this material. However, the physical and chemical treatment of natural fiber varies with the type of natural fiber. Natural fibers are usually prepared from agricultural waste, such as plant straw; therefore, they require treatment, which modifies their fiber size in conformance with application requirements. By contrast, chemical treatment involves surface modification; this process entails the utilization of varying concentrations of sodium hydroxide solutions, and it enhances the compatibility of the natural plant fibers with the resin matrix, which optimizes the properties of natural fiber concrete. Therefore, most of the most optimal preparation processes for natural fibers are conducted on a laboratory scale. For the production of natural fibers on an industrial scale, additional research on the optimization of production methods that can enhance the performance of natural fibers is required. The treatment of effluents, which is a process that characterizes the chemical production of natural fibers, also requires analysis.

Additionally, the intricate realm of manufacturing techniques for natural fiber concrete poses a formidable challenge. Within this composite, a multitude of minuscule fibers, randomly oriented and intricately dispersed, coalesce to form the fibrous matrix. In stark contrast,

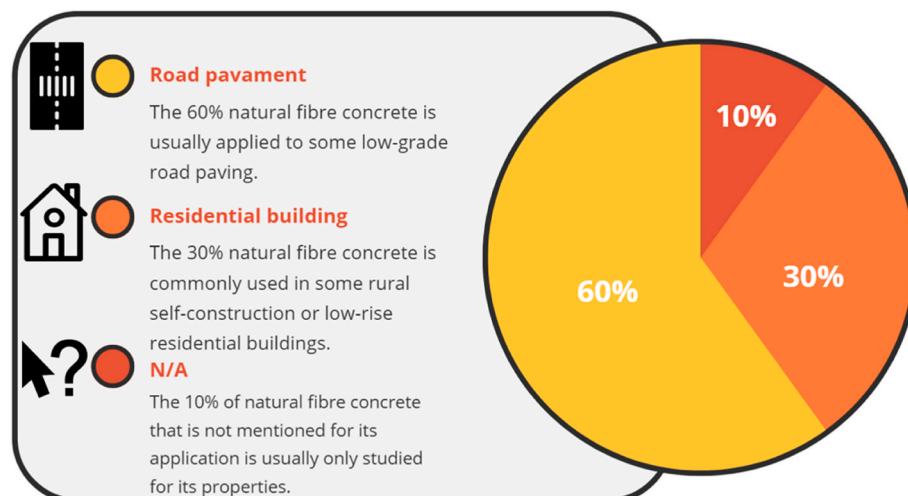


Fig. 4. Application of natural fiber concrete in different types of building projects.

traditional fiber-reinforced concrete is reliant on an irregular distribution of fibers, each free from conformity with a uniform arrangement (Devi et al., 2022). These fibers assume the pivotal role of enhancing flexural, tensile, and impact strengths, thereby enabling the production of structural concrete elements. From classical architectural forms to avant-garde designs, fiber concrete has emerged as a ubiquitous and sustainable construction material, adept at not only mitigating environmental concerns but also advancing construction practices. However, the actualization of these multifaceted applications hinges critically upon the precision of manufacturing techniques employed in the creation of fiber-reinforced concrete. Extensive investigations, as undertaken by Reichenbach et al. (2021), have revealed that the choice of manufacturing method exerts a profound impact on the resultant performance of fiber-reinforced concrete. In a controlled laboratory environment, Mohan et al. (2020) meticulously devised fiber-reinforced concrete using the batch mixing method, incorporating fibers of 12 mm and 30 mm length, constituting 8% of the volume content. Subsequent testing, following standard curing conditions, unveiled marked enhancements in compressive and flexural strengths when compared to conventional concrete, thereby firmly ensuring the realization of desired performance attributes. Conversely, continuous mixing methods present an avenue for scalability and efficiency, prerequisites for meeting the demands of large-scale infrastructure projects (Shaikh et al., 2023). Moreover, precision fiber dispersion techniques, encompassing high shear mixing and mechanical blending, represent indispensable means of achieving homogeneity within fiber concrete, consequently bolstering its structural robustness and durability (Allam et al., 2022). Proficiency in controlling the degree of fiber dispersion yields innovative solutions for addressing durability concerns linked with weathering, moisture infiltration, and chemical exposure, thus expansively broadening the application horizons of natural fiber concrete.

In summary, most of the literature on the mechanical properties of natural fiber concrete and on the application of its sustainability in practical engineering are still in the laboratory analysis stage. Therefore, to promote the application of natural fiber concrete in road projects, housing projects, and other engineering projects, the following research fields should be investigated:

- 1) The chemical interaction between natural fibers and the cement matrix, which can promote effective compatibility between the natural fibers and cement matrix; this field is necessary because fiber degradation affects alkaline degradation.
- 2) The natural fiber quality, which can ensure minimal variation in the properties of natural fiber, thus affecting their mechanical performance.
- 3) The durability of natural fiber concrete; however, this material can effectively control concrete cracking.
- 4) The life cycle analysis of natural fiber concrete and its application in different building typologies, which can advance its application in practical building projects and promote green building development worldwide.

6. Perspectives for future research

Research on the microstructure of natural fiber concrete at various scales, from the fiber-matrix interface at the nanoscale to the crack extension mode at the macroscopic scale, can enable researchers to precisely control the mechanical properties of natural fiber concrete (Raja et al., 2021). Meanwhile, the interaction between the microstructure and mechanical property behavior of natural fiber concrete bears a striking resemblance to the principles of bionics, and when the properties of natural fiber concrete are investigated from a bionic perspective, a novel research direction for the design of innovative natural fiber concrete materials is developed. Ha and Lu (2020) comprehensively reviewed the energy absorbing applications of biomimetic structures and materials, describing the flora and fauna. The

unique characteristics and mechanical properties of biostructures, such as plants and animals, and the fact that effective energy absorbers can be designed by mimicking the corresponding properties and characteristics provide valuable insights into the potential of biomimicry. Moreover, the self-repair mechanisms and adaptive responses of natural systems to environmental changes provide a double guarantee for matrix performance stability, such as the utilization of fibers to enhance healing cracks in concrete, the prevention of immediate damage to concrete by automatically sealing cracks, and the creation of a protective barrier against environmental attack (Manvith Kumar Reddy et al., 2020; Wu et al., 2023). In future studies, researchers can delve into the specific characteristics of plants (e.g., vascular networks) to mimic self-healing mechanisms and apply them to practical natural fiber concrete applications to further develop innovative natural fiber concrete materials.

Natural fiber concrete has been utilized in traditional engineering for non-structural components and thermal insulation, demonstrating its ability to reduce carbon emissions and enhance energy efficiency (Kodur et al., 2023). With the popularity of smart buildings, researchers have proposed to integrate natural fiber materials with smart building practices, a synergistic model that opens up novel avenues for innovative construction methods and building design. Monazami et al. (2022) utilized natural fiber concrete materials with embedded sensors to monitor changes in pavement temperature, humidity, and strain during the construction process, enabling the real-time performance of carbon fiber-reinforced concrete to be assessed. In addition, due to the sustainability and versatility of natural fibers, connecting them with sensors prevents the destruction of their own structure (Dadkhah and Tulliani, 2022). Moreover, IoT integration facilitates real-time data collection and communication, enabling buildings to adapt to changing conditions and rationally utilize data resources to accomplish self-optimization (Mishra et al., 2022). Dinesh et al. (2023) developed a self-sensing cement composite containing carbon fibers that can be utilized for structural health monitoring, demonstrating the feasibility of sensors supporting fiber concrete for infrastructure monitoring. Therefore, attempts can be made to explore the integration of natural fiber concrete materials with the IoT, focusing on the development of integrated systems for real-time data collection in natural fiber concrete structures.

7. Conclusion

This study conducts an in-depth analysis of the potential of natural fiber concrete as a sustainable building material for green building applications and of its own sustainability assessment using the literature review method. Despite the growing interest in green materials, there is still a lack of research dedicated to analyzing the performance, sustainability, applications, challenges, and opportunities of sustainable materials, especially with regard to natural fiber concrete. Herein, the main findings can be summarized as follows:

- 1) Natural fibers reduce concrete cracking and increase tensile strength. Fibers enhance the internal stress distribution and improve the stability of concrete; however, the tensile strength is reduced. Fibers can enhance the thermal insulation and noise reduction of concrete by reducing its density.
- 2) 85.7% of natural fiber concrete exhibits satisfactory environmental benefits in reducing carbon dioxide emissions and promoting the recycling of agricultural waste. However, natural fiber concrete should still consider the adverse environmental pollution occasioned by greenhouse gases emitted from agricultural waste disposal, thus only 28.6% of natural fiber concrete materials exhibit satisfactory economic benefits. 43% of the studies indicate that natural fiber concrete is socially sustainable; however, concrete composed of flax fiber may harm the ecology and soil, which may negatively affect human health.
- 3) According to the study, 60% of natural fiber concrete is utilized in road works and 30% in residential buildings. However, in residential

construction, natural fiber concrete can only be utilized as part of building components such as roof panels, siding, and exterior walls, and exhibits poor thermal insulation properties. In addition, the preparation process of natural fibers is mainly based on the laboratory scale, and the realization of the industrial production of natural fibers requires further research.

- 4) Because fiber degradation exerts a highly considerable influence on alkaline degradation, research on the chemical relationship between natural fibers and the cement matrix should be advanced. Concrete stability is affected by the properties of natural fibers, and research on the quality and compressive strength as well as on the durability of natural fibers should be increased. A life cycle analysis pertaining to the application of natural fiber concrete in different construction projects can promote the development of green buildings worldwide.

In conclusion, this study comprehensively explores the potential of natural fiber concrete as a sustainable alternative to traditional materials, including fresh properties, mechanical properties, durability, thermal conductivity, and acoustic properties; furthermore, the study analyzes the current state of the existing literature on the sustainability of natural fiber concrete in regard to environmental, economic, and social aspects. Moreover, barriers limiting the application of various natural fiber concretes as building materials are considered, and their potential is summarized. However, natural fiber concrete is subjected to a number of challenges that hinder industrial production, such as practical guidance and wastewater treatment. In addition, to realize the broadened application of natural fiber concrete in the building materials domain, future researchers can conduct further studies on both material property enhancement and on the sustainable transformation of natural fiber concrete.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

- Abdalla, A.N., Nazir, M.S., Tao, H., Cao, S., Ji, R., Jiang, M., Yao, L., 2021. Integration of energy storage system and renewable energy sources based on artificial intelligence: an overview. *J. Energy Storage* 40, 102811. <https://doi.org/10.1016/j.est.2021.102811>.
- Abdullah, A., Ahmed, A., Akhter, P., Razzaq, A., Hussain, M., Hossain, N., Abu Bakar, M. S., Khuram, S., Majeed, K., Park, Y.-K., 2021. Potential for sustainable utilisation of agricultural residues for bioenergy production in Pakistan: an overview. *J. Clean. Prod.* 287, 125047 <https://doi.org/10.1016/j.jclepro.2020.125047>.
- Abdur Rahman, M., Haque, S., Athikesavan, M.M., Kamaludeen, M.B., 2023. A review of environmental friendly green composites: production methods, current progresses, and challenges. *Environ. Sci. Pollut. Control Ser.* 30, 16905–16929. <https://doi.org/10.1007/s11356-022-24879-5>.
- Abrrar, M., 2021. Workability of banana fibers reinforced concrete for easy pouring. *3rd Conf. Sustain. Civ. Eng* 5–9.
- Achal, V., Mukherjee, A., Reddy, M.S., 2011. Effect of calcifying bacteria on permeation properties of concrete structures. *J. Ind. Microbiol. Biotechnol.* 38, 1229–1234. <https://doi.org/10.1007/s10295-010-0901-8>.
- Adriaanse L, S., Rensleigh, C., 2013. Web of science, scopus and Google scholar. *Electron. Libr.* 31, 727–744. <https://doi.org/10.1108/EL-12-2011-0174>.
- Affan, M., Ali, M., 2022. Experimental investigation on mechanical properties of jute fiber reinforced concrete under freeze-thaw conditions for pavement applications. *Construct. Build. Mater.* 323, 126599 <https://doi.org/10.1016/j.conbuildmat.2022.126599>.
- Afraz, A., Ali, M., 2021. Effect of banana fiber on flexural properties of fiber reinforced concrete for sustainable construction. *Engineering Proceedings* 12, 63. <https://doi.org/10.3390/engproc2021012063>.
- Ahmad, J., Zhou, Z., 2022. Mechanical properties of natural as well as synthetic fiber reinforced concrete: a review. *Construct. Build. Mater.* 333, 127353 <https://doi.org/10.1016/j.conbuildmat.2022.127353>.
- Ahmad, J., Manan, A., Ali, A., Khan, M.W., Asim, M., Zaid, O.J.C.E.A., 2020a. A study on mechanical and durability aspects of concrete modified with steel fibers (SFs). *Civil Engineering and Architecture* 8, 814–823. <https://doi.org/10.13189/cea.2020.080508>.
- Ahmad, W., Farooq, S.H., Usman, M., Khan, M., Ahmad, A., Aslam, F., Yousef, R.A., Abduljabbar, H.A., Sufian, M., 2020b. Effect of coconut fiber length and content on properties of high strength concrete. *Materials* 13, 1075. <https://doi.org/10.3390/ma13051075>.
- Ahmad, J., Zaid, O., Siddique, M.S., Aslam, F., Alabduljabbar, H., Khedher, K.M., 2021a. Mechanical and durability characteristics of sustainable coconut fibers reinforced concrete with incorporation of marble powder. *Mater. Res. Express* 8, 075505. <https://doi.org/10.1088/2053-1591/ac10d3>.
- Ahmad, M.R., Chen, B., Haque, M.A., Saleem Kazmi, S.M., Munir, M.J., 2021b. Development of plant-concrete composites containing pretreated corn stalk bio-aggregates and different type of binders. *Cement Concr. Compos.* 121, 104054 <https://doi.org/10.1016/j.cemconcomp.2021.104054>.
- Ahmad, J., Gonzalez-Lezcano, R.A., Majdi, A., Ben Kahla, N., Deifalla, A.F., El-Shorbagy, M.A., 2022a. Glass fibers reinforced concrete: overview on mechanical, durability and microstructure analysis. *Materials* 15, 5111. <https://doi.org/10.3390/ma15155111>.
- Ahmad, J., Majdi, A., Al-Fakih, A., Deifalla, A.F., Althoe, F., El Ouni, M.H., El-Shorbagy, M.A., 2022b. Mechanical and durability performance of coconut fiber reinforced concrete: a state-of-the-art review. *Materials* 15, 3601. <https://doi.org/10.3390/ma15103601>.
- Ahmad, J., Majdi, A., Elhag, A.B., Deifalla, A.F., Soomro, M., Isleem, H.F., Qaidi, S., 2022c. A step towards sustainable concrete with substitution of plastic waste in concrete: overview on mechanical, durability and microstructure analysis. *Crystals* 12, 944. <https://doi.org/10.3390/cryst12070944>.
- Ahmed, K.U., Geremew, A., Jemal, A., 2022. The comparative study on the performance of bamboo fiber and sugarcane bagasse fiber as modifiers in asphalt concrete production. *Heliyon* 8, e09842. <https://doi.org/10.1016/j.heliyon.2022.e09842>.
- Alam, M.A., Al Riyami, K., 2018. Shear strengthening of reinforced concrete beam using natural fibre reinforced polymer laminates. *Construct. Build. Mater.* 162, 683–696. <https://doi.org/10.1016/j.conbuildmat.2017.12.011>.
- Ali, B., Azab, M., Ahmed, H., Kurda, R., El Ouni, M.H., Elhag, A.B., 2022. Investigation of physical, strength, and ductility characteristics of concrete reinforced with banana (Musaceae) stem fiber. *J. Build. Eng.* 61, 105024 <https://doi.org/10.1016/j.jobe.2022.105024>.
- Allam, H., Duplan, F., Amziane, S., Burtshell, Y., 2022. Assessment of manufacturing process efficiency in the dispersion of carbon fibers in smart concrete by measuring AC impedance. *Cement Concr. Compos.* 127, 104394 <https://doi.org/10.1016/j.cemconcomp.2021.104394>.
- Alomayri, T., Ali, B., 2023. Effect of plant fiber type and content on the strength and durability performance of high-strength concrete. *Construct. Build. Mater.* 394, 132166 <https://doi.org/10.1016/j.conbuildmat.2023.132166>.
- Althoe, F., Zaid, O., de-Prado-Gil, J., Palencia, C., Ali, E., Hakeem, I., Martínez-García, R., 2022. Impact of sulfate activation of rice husk ash on the performance of high strength steel fiber reinforced recycled aggregate concrete. *J. Build. Eng.* 54, 104610 <https://doi.org/10.1016/j.jobe.2022.104610>.
- Amin, K.F., Asrafuzzaman, Sharif A., Md Enamul, H., 2021. In: Jawaid, M., Mavinkere Rangappa, S., Siengchin, S. (Eds.), *Bamboo/Bamboo Fiber Reinforced Concrete Composites and Their Applications in Modern Infrastructure*. Springer Singapore, Singapore, pp. 271–297. https://doi.org/10.1007/978-981-15-8489-3_15.
- Amin, M., Tayeh, B.A., Kandil, M.A., Agwa, I.S., Abdelmagied, M.F., 2022. Effect of rice straw ash and palm leaf ash on the properties of ultrahigh performance concrete. *Case Stud. Constr. Mater.* 17, e01266 <https://doi.org/10.1016/j.cscm.2022.e01266>.
- Anggraeni, S., Nandiyanto, A.B.D., Nurjamil, A.M., Wolio, N.A., Laila, R.N., Rohmah, S.I. A., Al Huseini, D.F., Azizah, N.N., 2022. Effect of sawdust, eggshells, rice, husks, and corn husks as fine aggregates on the mechanical properties of concrete. *J. Eng. Sci. Technol.* 17, 1810–1819.
- Arunachalam, K.P., Avudaiappan, S., Flores, E.I.S., Parra, P.F., 2023. Experimental study on the mechanical properties and microstructures of cenosphere concrete. *Materials* 16, 3518. <https://doi.org/10.3390/ma16093518>.
- Asdrubali, F., D'Alessandro, F., Schiavoni, S., 2015. A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies* 4, 1–17. <https://doi.org/10.1016/j.susmat.2015.05.002>.
- Asim, M., Uddin, G.M., Jamshaid, H., Raza, A., Zu, Rehman Tahir, Hussain, U., Satti, A. N., Hayat, N., Arafat, S.M., 2020. Comparative experimental investigation of natural fibers reinforced light weight concrete as thermally efficient building materials. *J. Build. Eng.* 31, 101411 <https://doi.org/10.1016/j.jobe.2020.101411>.
- Ataie, F., 2018. Influence of rice straw fibers on concrete strength and drying shrinkage. *Sustainability* 10, 2445. <https://doi.org/10.3390/su10072445>.
- B., S., Patil, N., Jaiswal, K.K., Gowrishankar, T.P., Selvakumar, K.K., Jyothi, M.S., Jyothilakshmi, R., Kumar, S., 2023. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: a review. *Construct. Build. Mater.* 368, 130457 <https://doi.org/10.1016/j.conbuildmat.2023.130457>.
- Bar-Ilan, J., 2008. Which h-index? — a comparison of WoS, scopus and Google scholar. *Scientometrics* 74, 257–271. <https://doi.org/10.1007/s11192-008-0216-y>.

- Bashir, A., Gupta, C., Abubakar, M., Abba, S., 2018. Analysis of Bamboo fibre reinforced beam. *J. Steel Struct. Constr.* 4, 2–7. <https://doi.org/10.4172/2472-0437.1000146>.
- Bhaskar, D., Suresh, G., Ganesamoorthy, R., Srinivasan, T., Dharmendra, B.V., Meenakshi, C.M., Selva Ganapathy, K., 2022. Behaviour of fibre length in banana fibre reinforced thermoplastic composites under high velocity impact performance. *Recent Advances in Materials and Modern Manufacturing* 1029–1037.
- Bhuvaneshwari, S., Hettiarachchi, H., Meegoda, J.N., 2019. Crop residue burning in India: policy challenges and potential solutions. *Int. J. Environ. Res. Publ. Health* 16, 832. <https://doi.org/10.3390/ijerph16050832>.
- Binici, H., Aksogan, O., Dincer, A., Luga, E., Eken, M., Isikaltun, O., 2020. The possibility of vermiculite, sunflower stalk and wheat stalk using for thermal insulation material production. *Therm. Sci. Eng. Prog.* 18, 100567 <https://doi.org/10.1016/j.tsep.2020.100567>.
- Bittner, C.M., Oettel, V., 2022. Fiber reinforced concrete with natural plant fibers—investigations on the application of bamboo fibers in ultra-high performance concrete. *Sustainability* 14. <https://doi.org/10.3390/su141912011>, 12011.
- Bumanis, G., Korjakins, A., Bajare, D., 2022. Environmental benefit of alternative binders in construction industry: life cycle assessment. *Environments* 9, 6. <https://doi.org/10.3390/environments9010006>.
- Cappucci, G.M., Ruffini, V., Barbieri, V., Siligardi, C., Ferrari, A.M., 2022. Life cycle assessment of wheat husk based agro-concrete block. *J. Clean. Prod.* 349, 131437 <https://doi.org/10.1016/j.jclepro.2022.131437>.
- Cavacini, A., 2015. What is the best database for computer science journal articles? *Scientometrics* 102, 2059–2071. <https://doi.org/10.1007/s11192-014-1506-1>.
- Chabannes, M., Bénézet, J.-C., Clerc, L., Garcia-Diaz, E., 2014. Use of raw rice husk as natural aggregate in a lightweight insulating concrete: an innovative application. *Construct. Build. Mater.* 70, 428–438. <https://doi.org/10.1016/j.conbuildmat.2014.07.025>.
- Chen, J., Elbashiry, E.M.A., Yu, T., Ren, Y., Guo, Z., Liu, S., 2018. Research progress of wheat straw and rice straw cement-based building materials in China. *Mag. Concr. Res.* 70, 84–95. <https://doi.org/10.1680/jmacr.17.00064>.
- Chen, W., Jin, R., Xu, Y., Wanatowski, D., Li, B., Yan, L., Pan, Z., Yang, Y., 2019a. Adopting recycled aggregates as sustainable construction materials: a review of the scientific literature. *Construct. Build. Mater.* 218, 483–496. <https://doi.org/10.1016/j.conbuildmat.2019.05.130>.
- Chen, Z., Chen, Z., Yi, J., Feng, D., 2019b. Preparation method of corn stalk fiber material and its performance investigation in asphalt concrete. *Sustainability* 11, 4050. <https://doi.org/10.3390/su11154050>.
- Chen, C., Yang, Y., Zhou, Y., Xue, C., Chen, X., Wu, H., Sui, L., Li, X., 2020. Comparative analysis of natural fiber reinforced polymer and carbon fiber reinforced polymer in strengthening of reinforced concrete beams. *J. Clean. Prod.* 263, 121572 <https://doi.org/10.1016/j.jclepro.2020.121572>.
- Chen, L., Msigwa, G., Yang, M., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022. Strategies to achieve a carbon neutral society: a review. *Environ. Chem. Lett.* 20, 2277–2310. <https://doi.org/10.1007/s10311-022-01435-8>.
- Chen, L., Chen, Z., Zhang, Y., Liu, Y., Osman, A.I., Farghali, M., Hua, J., Al-Fatesh, A., Ihara, I., Rooney, D.W., Yap, P.-S., 2023a. Artificial intelligence-based solutions for climate change: a review. *Environ. Chem. Lett.* 21, 2525–2557. <https://doi.org/10.1007/s10311-023-01617-y>.
- Chen, L., Huang, L., Hua, J., Chen, Z., Wei, L., Osman, A.I., Fawzy, S., Rooney, D.W., Dong, L., Yap, P.-S., 2023b. Green construction for low-carbon cities: a review. *Environ. Chem. Lett.* 21, 1627–1657. <https://doi.org/10.1007/s10311-022-01544-4>.
- Chin, S.C., Tee, K.F., Tong, F.S., Doh, S.I., Gimbum, J., 2020. External strengthening of reinforced concrete beam with opening by bamboo fiber reinforced composites. *Mater. Struct.* 53, 141. <https://doi.org/10.1617/s11527-020-01572-y>.
- Collivignarelli, M.C., Abbà, A., Carnevale Miino, M., Cillari, G., Ricciardi, P., 2021. A review on alternative binders, admixtures and water for the production of sustainable concrete. *J. Clean. Prod.* 295, 126408 <https://doi.org/10.1016/j.jclepro.2021.126408>.
- Costa Junior, A., Barreto, A., Rosa, D., Maia, F., Lomonaco, D., Mazzetto, S., 2015. Thermal and mechanical properties of biocomposites based on a cashew nut shell liquid matrix reinforced with bamboo fibers. *J. Compos. Mater.* 49, 2203–2215. <https://doi.org/10.1177/0021998314545182>.
- Cruz, J., Figueiro, R., 2016. Surface modification of natural fibers: a review. *Procedia Eng.* 155, 285–288. <https://doi.org/10.1016/j.proeng.2016.08.030>.
- Dadkhah, M., Tulliani, J.-M., 2022. Damage management of concrete structures with engineered cementitious materials and natural fibers: a review of potential uses. *Sustainability* 14, 3917. <https://doi.org/10.3390/su14073917>.
- Dai, G., Zhang, Z., Du, W., Li, Z., Gao, W., Li, L., 2019. Conversion of skin collagen fibrous material waste to an oil sorbent with pH-responsive switchable wettability for high-efficiency separation of oil/water emulsions. *J. Clean. Prod.* 226, 18–27. <https://doi.org/10.1016/j.jclepro.2019.03.287>.
- Danso, H., 2018. Identification of key indicators for sustainable construction materials. *Adv. Mater. Sci. Eng.*, 6916258 <https://doi.org/10.1155/2018/6916258>, 2018.
- Danso, H., 2020. Effect of rice husk on the mechanical properties of cement-based mortar. *J. Inst. Eng.: Series D* 101, 205–213. <https://doi.org/10.1007/s40033-020-00228-z>.
- Darsana, P., Abraham, R., Joseph, A., Jasheela, A., Binuraj, P.R., Sarma, J., 2016. Development of coir-fibre cement composite roofing tiles. *Procedia Technology* 24, 169–178. <https://doi.org/10.1016/j.protcy.2016.05.024>.
- Devi, C., Vijayan, D.S., Nagalingam, R., Arvindan, S., 2022. A review of the implementations of glass fiber in concrete technology. *Mater. Today: Proc.* 62, 2010–2015. <https://doi.org/10.1016/j.matpr.2022.02.293>.
- Dhasmana, A., Singh, S.P., 2023. Long-term mechanical characteristics of fibre reinforced metakaolin-based geopolymer concrete: a review. *Mater. Today: Proc.* <https://doi.org/10.1016/j.matpr.2023.07.030>.
- Dinesh, A., Suj, D., Pichumani, M., 2023. Development of a comprehensive methodology for the design and fabrication of carbon fiber integrated cement composite toward health monitoring of structural components. *Eng. Struct.* 277, 115453 <https://doi.org/10.1016/j.engstruct.2022.115453>.
- Ding, G.K.C., 2014. In: Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhães, A. (Eds.), 3 - Life Cycle Assessment (LCA) of Sustainable Building Materials: an Overview. Woodhead Publishing, pp. 38–62. <https://doi.org/10.1533/9780857097729.1.38>.
- Duong, N.T., Satomi, T., Takahashi, H., 2021a. Potential of corn husk fiber for reinforcing cemented soil with high water content. *Construct. Build. Mater.* 271, 121848 <https://doi.org/10.1016/j.conbuildmat.2020.121848>.
- Duong, N.T., Satomi, T., Takahashi, H., 2021b. Study on the Compressive and Tensile Strength Behaviors of Corn Husk Fiber-Cement Stabilized Soil. Computational Intelligence Methods for Green Technology and Sustainable Development, pp. 492–503. https://doi.org/10.1007/978-3-030-63234-1_42.
- Ede, A.N., Oshogbun, O., Olofinnade, O., Jolayemi, K., Oyeibisi, S.O., Mark, O.G., Awoyera, P.O., 2019. Effects of bamboo fibers and limestone powder on fresh properties of self-compacting concrete. In: *Proceedings of 10th Interdependence between Structural Engineering and Construction Management, ISEC10*.
- Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., Garnier, C., 2023. A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. *Results in Engineering* 19, 101271. <https://doi.org/10.1016/j.rineng.2023.101271>.
- Endale, S.A., Taffese, W.Z., Vo, D.-H., Yehualaw, M.D., 2023. Rice husk ash in concrete. *Sustainability* 15, 137. <https://doi.org/10.3390/su15010137>.
- Ernest, E.M., Peter, A.C., 2022. Application of selected chemical modification agents on banana fibre for enhanced composite production. *Cleaner Materials* 5, 100131. <https://doi.org/10.1016/j.clema.2022.100131>.
- Fantilli, A.P., Mancinelli, O., Chiaia, B., 2019. The carbon footprint of normal and high-strength concrete used in low-rise and high-rise buildings. *Case Stud. Constr. Mater.* 11, e00296 <https://doi.org/10.1016/j.cscm.2019.e00296>.
- Farghali, M., Osman, A.I., Mohamed, I.M.A., Chen, Z., Chen, L., Ihara, I., Yap, P.-S., Rooney, D.W., 2023. Strategies to save energy in the context of the energy crisis: a review. *Environ. Chem. Lett.* 21, 2003–2039. <https://doi.org/10.1007/s10311-023-01591-5>.
- Farhan, K.Z., Johari, M.A.M., Demirboğa, R., 2021. Impact of fiber reinforcements on properties of geopolymer composites: a review. *J. Build. Eng.* 44, 102628 <https://doi.org/10.1016/j.jobbe.2021.102628>.
- Farooqi, M.U., Ali, M., 2018a. Contribution of plant fibers in improving the behavior and capacity of reinforced concrete for structural applications. *Construct. Build. Mater.* 182, 94–107. <https://doi.org/10.1016/j.conbuildmat.2018.06.041>.
- Farooqi, M.U., Ali, M., 2018b. Effect of fibre content on compressive strength of wheat straw reinforced concrete for pavement applications. *IOP Conf. Ser. Mater. Sci. Eng.* 422, 012014 <https://doi.org/10.1088/1757-899X/422/1/012014>.
- Farooqi, M.U., Ali, M., 2019. Effect of pre-treatment and content of wheat straw on energy absorption capability of concrete. *Construct. Build. Mater.* 224, 572–583. <https://doi.org/10.1016/j.conbuildmat.2019.07.086>.
- Farooqi, M.U., Ali, M., 2022. A study on natural fibre reinforced concrete from materials to structural applications. *Arabian J. Sci. Eng.* 48, 4471–4491. <https://doi.org/10.1007/s13369-022-06977-1>.
- Farooqi, M.U., Ali, M., 2023. A study on natural fibre reinforced concrete from materials to structural applications. *Arabian J. Sci. Eng.* 48, 4471–4491. <https://doi.org/10.1007/s13369-022-06977-1>.
- Florea, I., Manea, D.L., 2019. Analysis of thermal insulation building materials based on natural fibers. *Procedia Manuf.* 32, 230–235. <https://doi.org/10.1016/j.promfg.2019.02.207>.
- Geremew, A., De Winne, P., Demissie, T.A., De Backer, H., 2021. Treatment of natural fiber for application in concrete pavement. *Adv. Civ. Eng.* 2021, 6667965 <https://doi.org/10.1155/2021/6667965>.
- Geremew, A., De Winne, P., Demissie, T.A., De Backer, H., 2022. Characterization of wheat straw fiber grown around jimma zone, Ethiopia. *J. Nat. Fibers* 1–10. <https://doi.org/10.1080/15440478.2022.2134268>.
- Griffiths, S., Sovacool, B.K., Furszyfer Del Rio, D.D., Foley, A.M., Bazilian, M.D., Kim, J., Uratani, J.M., 2023. Decarbonizing the cement and concrete industry: a systematic review of socio-technical systems, technological innovations, and policy options. *Renew. Sustain. Energy Rev.* 180, 113291 <https://doi.org/10.1016/j.rser.2023.113291>.
- Ha, N.S., Lu, G., 2020. A review of recent research on bio-inspired structures and materials for energy absorption applications. *Compos. B Eng.* 181, 107496 <https://doi.org/10.1016/j.compositesb.2019.107496>.
- Ha, N.S., Marundrury, S.S., Pham, T.M., Pournasiri, E., Shi, F., Hao, H., 2022. Effect of grounded blast furnace slag and rice husk ash on performance of ultra-high-performance concrete (UHPC) subjected to impact loading. *Construct. Build. Mater.* 329, 127213 <https://doi.org/10.1016/j.conbuildmat.2022.127213>.
- Hakeem, I.Y., Agwa, I.S., Tayeh, B.A., Abd-Elrahman, M.H., 2022. Effect of using a combination of rice husk and olive waste ashes on high-strength concrete properties. *Case Stud. Constr. Mater.* 17, e01486 <https://doi.org/10.1016/j.cscm.2022.e01486>.
- Hamada, H.M., Shi, J., Al Jawahery, M.S., Majidi, A., Yousif, S.T., Kaplan, G., 2023. Application of natural fibres in cement concrete: a critical review. *Mater. Today Commun.* 35, 105833 <https://doi.org/10.1016/j.mtcomm.2023.105833>.
- Hamzeh, Y., Ziabari, K.P., Torkaman, J., Ashori, A., Jafari, M., 2013. Study on the effects of white rice husk ash and fibrous materials additions on some properties of

- fiber-cement composites. *J. Environ. Manag.* 117, 263–267. <https://doi.org/10.1016/j.jenvman.2013.01.002>.
- Hay, R., Ostertag, C.P., 2018. Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics. *Build. Environ.* 142, 327–341. <https://doi.org/10.1016/j.buildenv.2018.06.024>.
- He, Z., Shen, A., Wu, H., Wang, W., Wang, L., Yao, C., Wu, J., 2021. Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials. *Construct. Build. Mater.* 274, 122113 <https://doi.org/10.1016/j.conbuildmat.2020.122113>.
- Hesami, S., Ahmadi, S., Nematzadeh, M., 2014. Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement. *Construct. Build. Mater.* 53, 680–691. <https://doi.org/10.1016/j.conbuildmat.2013.11.070>.
- Huner, U., 2015. Effect of water absorption on the mechanical properties of flax fiber reinforced epoxy composites. *Advances in Science and Technology Research Journal* 9, 1–6. <https://doi.org/10.12913/22998624/2357>.
- Ibitoye, S.E., Ajimotokan, H.A., Adeleke, A.A., Loha, C., 2023. Effect of densification process parameters on the physico-mechanical properties of composite briquettes of corn cob and rice husk. *Mater. Today: Proc.* <https://doi.org/10.1016/j.matpr.2023.08.253>.
- Imanzadeh, S., Jarno, A., Hibouche, A., Bouarar, A., Taibi, S., 2020. Ductility analysis of vegetal-fiber reinforced raw earth concrete by mixture design. *Construct. Build. Mater.* 239, 117829 <https://doi.org/10.1016/j.conbuildmat.2019.117829>.
- Imraan, M., Ilyas, R.A., Norfarhana, A.S., Bangar, S.P., Knight, V.F., Norrahim, M.N.F., 2023. Sugar palm (Arenca pinnata) fibers: new emerging natural fibre and its relevant properties, treatments and potential applications. *J. Mater. Res. Technol.* 24, 4551–4572. <https://doi.org/10.1016/j.jmrt.2023.04.056>.
- Jameel, M.S., Khan, M.J., Raza, A., Khan, S.R., 2022. Assessment of workability of banana fiber reinforced concrete for easy pouring. *INTERNATIONAL AEGEAN SYMPOSIUMS* 61–65.
- Jamshaid, H., Mishra, R.K., Raza, A., Hussain, U., Rahman, M.L., Nazari, S., Chandan, V., Muller, M., Choteborsky, R., 2022. Natural cellulosic fiber reinforced concrete: influence of fiber type and loading percentage on mechanical and water absorption performance. *Materials* 15, 874. <https://doi.org/10.3390/ma15030874>.
- Jarabo, R., Monte, M.C., Fuente, E., Santos, S.F., Negro, C., 2013. Corn stalk from agricultural residue used as reinforcement fiber in fiber-cement production. *Ind. Crop. Prod.* 43, 832–839. <https://doi.org/10.1016/j.indcrop.2012.08.034>.
- Jiang, D., Lv, S., Jiang, D., Xu, H., Kang, H., Song, X., He, S., 2023. Effect of modification methods on water absorption and strength of wheat straw fiber and its cement-based composites. *J. Build. Eng.* 71, 106466 <https://doi.org/10.1016/j.job.2023.106466>.
- Kajaste, R., Hurme, M., 2016. Cement industry greenhouse gas emissions – management options and abatement cost. *J. Clean. Prod.* 112, 4041–4052. <https://doi.org/10.1016/j.jclepro.2015.07.055>.
- Kannan, V., 2018. Strength and durability performance of self compacting concrete containing self-compacted rice husk ash and metakaolin. *Construct. Build. Mater.* 160, 169–179. <https://doi.org/10.1016/j.conbuildmat.2017.11.043>.
- Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., Vijay, V., Kumar, V., Kumar Vijay, V., Pant, D., 2020. Valorization of agricultural waste for biogas based circular economy in India: a research outlook. *Bioresour. Technol.* 304, 123036 <https://doi.org/10.1016/j.biortech.2020.123036>.
- Kapur, A., van Oss, H.G., Keoleian, G., Kesler, S.E., Kendall, A., 2009. The contemporary cement cycle of the United States. *J. Mater. Cycles Waste Manag.* 11, 155–165. <https://doi.org/10.1007/s10163-008-0229-x>.
- Kesavaram S., 2017. Studies on Metakaolin based banana fibre reinforced concrete. *Int. J. Civ. Eng. Technol.* 8, 532–543. Available online at: <http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=1>.
- Khan, M.W., Ali, Y., 2020. Sustainable construction. *Construct. Innovat.* 20, 191–207. <https://doi.org/10.1108/CI-05-2019-0040>.
- Khan, M., Rehman, A., Ali, M., 2020. Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road. *Construct. Build. Mater.* 244, 118382 <https://doi.org/10.1016/j.conbuildmat.2020.118382>.
- Khelifi, F., Lecompte, T., Perrot, A., Ausias, G., 2016. Mechanical enhancement of cement-stabilized soil by flax fibre reinforcement and extrusion processing. *Mater. Struct.* 49, 1143–1156. <https://doi.org/10.1617/s11527-015-0564-z>.
- Kodur, V., Venkatachari, S., Bhatt, P., Matsagar, V.A., Singh, S.B., 2023. Fire resistance evaluation of concrete beams and slabs incorporating natural fiber-reinforced polymers. *Polymers* 15, 755. <https://doi.org/10.3390/polym15030755>.
- Korjenic, A., Zach, J., Hroudová, J., 2016. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. *Energy Build.* 116, 45–58. <https://doi.org/10.1016/j.enbuild.2015.12.037>.
- Koushkbaghi, M., Kazemi, M.J., Mosavi, H., Mohseni, E., 2019. Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Construct. Build. Mater.* 202, 266–275. <https://doi.org/10.1016/j.conbuildmat.2018.12.224>.
- Kouta, N., Saliba, J., Saiyouri, N., 2020. Effect of flax fibers on early age shrinkage and cracking of earth concrete. *Construct. Build. Mater.* 254, 119315 <https://doi.org/10.1016/j.conbuildmat.2020.119315>.
- Kouta, N., Saliba, J., Saiyouri, N., 2021. Fracture behavior of flax fibers reinforced earth concrete. *Eng. Fract. Mech.* 241, 107378 <https://doi.org/10.1016/j.engfractmech.2020.107378>.
- Kumar, N., Kandasami, R.K., Singh, S., 2022. Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction – a critical review. *Construct. Build. Mater.* 347, 128606 <https://doi.org/10.1016/j.conbuildmat.2022.128606>.
- Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C., Bertron, A., 2016. Plant aggregates and fibers in earth construction materials: a review. *Construct. Build. Mater.* 111, 719–734. <https://doi.org/10.1016/j.conbuildmat.2016.02.119>.
- Laborel-Préneron, A., Magniont, C., Aubert, J.-E., 2018. Characterization of barley straw, hemp shiv and corn cob as resources for bioaggregate based building materials. *Waste and Biomass Valorization* 9, 1095–1112. <https://doi.org/10.1007/s12649-017-9895-z>.
- Lahououi, M., Ben Arfi, R., Fois, M., Ibos, L., Ghorbal, A., 2020. Investigation of fiber surface treatment effect on thermal, mechanical and acoustical properties of date palm fiber-reinforced cementitious composites. *Waste and Biomass Valorization* 11, 4441–4455. <https://doi.org/10.1007/s12649-019-00745-3>.
- Lai, P., Zhi, X., Shen, S., Wang, Z., Yu, P., 2019. Strength and damping properties of cementitious composites incorporating original and alkali treated flax fibers. *Appl. Sci.* 9, 2002. <https://doi.org/10.3390/app9102002>.
- Lau, K.-t., Hung, P.-y., Zhu, M.-H., Hui, D., 2018. Properties of natural fibre composites for structural engineering applications. *Compos. B Eng.* 136, 222–233. <https://doi.org/10.1016/j.compositesb.2017.10.038>.
- Lei, L., Li, R., Fuddini, A., 2020. Influence of maltodextrin retarder on the hydration kinetics and mechanical properties of Portland cement. *Cement Concr. Compos.* 114, 103774 <https://doi.org/10.1016/j.cemconcomp.2020.103774>.
- Lertwattanaruk, P., Suntijitto, A., 2015. Properties of natural fiber cement materials containing coconut coir and oil palm fibers for residential building applications. *Construct. Build. Mater.* 94, 664–669. <https://doi.org/10.1016/j.conbuildmat.2015.07.154>.
- Li, J., 2019. Study on mechanical properties of bamboo fiber asphalt concrete. *J. Shandong Agric. Univ. (Nat. Sci. Ed.)* 50, 593–596.
- Li, Z., He, X.Z., Cai, Z.M., Wang, R., Xiao, Y., 2021. Mechanical properties of engineered bamboo boards for glulam structures. *J. Mater. Civ. Eng.* 33, 04021058 [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003657](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003657).
- Liu, W., Chen, T., Wen, X., Qiu, R., Zhang, X., 2014. Enhanced mechanical properties and water resistance of bamboo fiber-unsaturated polyester composites coupled by isocyanatoethyl methacrylate. *Wood Sci. Technol.* 48, 1241–1255. <https://doi.org/10.1007/s00226-014-0668-6>.
- Liu, C., Zhang, W., Liu, H., Zhu, C., Wu, Y., He, C., Wang, Z., 2022a. Recycled aggregate concrete with the incorporation of rice husk ash: mechanical properties and microstructure. *Construct. Build. Mater.* 351, 128934 <https://doi.org/10.1016/j.conbuildmat.2022.128934>.
- Liu, T., Chen, L., Yang, M., Sandanayake, M., Miao, P., Shi, Y., Yap, P.-S., 2022b. Sustainability considerations of green buildings: a detailed overview on current advancements and future considerations. *Sustainability* 14, 14393. <https://doi.org/10.3390/su142114393>.
- Luo, Z., Li, P., Cai, D., Chen, Q., Qin, P., Tan, T., Cao, H., 2017. Comparison of performances of corn fiber plastic composites made from different parts of corn stalk. *Ind. Crop. Prod.* 95, 521–527. <https://doi.org/10.1016/j.indcrop.2016.11.005>.
- Madurwar, M.V., Ralegaonkar, R.V., Mandavgane, S.A., 2013. Application of agro-waste for sustainable construction materials: a review. *Construct. Build. Mater.* 38, 872–878. <https://doi.org/10.1016/j.conbuildmat.2012.09.011>.
- Maithil, P., Gupta, P., Chandravanshi, M.L., 2023. Study of mechanical properties of the natural-synthetic fiber reinforced polymer matrix composite. *Mater. Today: Proc.* <https://doi.org/10.1016/j.matpr.2023.01.245>.
- Manvith Kumar Reddy, C., Ramesh, B., Macrin, D., 2020. Effect of crystalline admixtures, polymers and fibers on self healing concrete - a review. *Mater. Today: Proc.* 33, 763–770. <https://doi.org/10.1016/j.matpr.2020.06.122>.
- Maraveas, C., 2020. Production of sustainable construction materials using agro-wastes. *Materials* 13, 262. <https://doi.org/10.3390/ma13020262>.
- Marques, B., Almeida, J., Tadeu, A., António, J., Santos, M.I., de Brito, J., Oliveira, M., 2021. Rice husk cement-based composites for acoustic barriers and thermal insulating layers. *J. Build. Eng.* 39, 102297 <https://doi.org/10.1016/j.job.2021.102297>.
- Martinelli, F.R.B., Ribeiro, F.R.C., Marvila, M.T., Monteiro, S.N., Filho, FdCG., Azevedo, ARGd, 2023. A review of the use of coconut fiber in cement composites. *Polymers* 15, 1309. <https://doi.org/10.3390/polym15051309>.
- Mei, Z., Xu, M., Luo, S., Tan, Y., Li, H., 2022. Concrete formwork reuse in a supply chain with dynamic changes using ABMS and discrete events. *J. Clean. Prod.* 332, 130038 <https://doi.org/10.1016/j.jclepro.2021.130038>.
- Merta, I., Mladenović, A., Turk, J., Šajna, A., Mauko Pranjić, A., 2018. Life cycle assessment of natural fibre reinforced cementitious composites. *Key Eng. Mater.* 761, 204–209. <https://doi.org/10.4028/www.scientific.net/KEM.761.204>.
- Mishra, M., Lourenço, P.B., Ramana, G.V., 2022. Structural health monitoring of civil engineering structures by using the internet of things: a review. *J. Build. Eng.* 48, 103954 <https://doi.org/10.1016/j.job.2021.103954>.
- Mistri, A., Bhattacharyya, S.K., Dhani, N., Mukherjee, A., Barai, S.V., 2020. A review on different treatment methods for enhancing the properties of recycled aggregates for sustainable construction materials. *Construct. Build. Mater.* 233, 117894 <https://doi.org/10.1016/j.conbuildmat.2019.117894>.
- Mohammed, L., Ansari, M.N.M., Pua, G., Jawaid, M., Islam, M.S., 2015. A review on natural fiber reinforced polymer composite and its applications. *International Journal of Polymer Science*, 243947. <https://doi.org/10.1155/2015/243947>.
- Mohan, A., Karthika, S., Ajith, J., dhal, L., Tholkapiyan, M., 2020. Investigation on ultra high strength slurry infiltrated multiscale fibre reinforced concrete. *Mater. Today: Proc.* 22, 904–911. <https://doi.org/10.1016/j.matpr.2019.11.102>.
- Momoh, E.O., Osofero, A.I., 2019. Behaviour of oil palm broom fibres (OPBF) reinforced concrete. *Construct. Build. Mater.* 221, 745–761. <https://doi.org/10.1016/j.conbuildmat.2019.06.118>.
- Monazami, M., Sharma, A., Gupta, R., 2022. Evaluating performance of carbon fiber-reinforced pavement with embedded sensors using destructive and non-destructive

- testing. *Case Stud. Constr. Mater.* 17, e01460 <https://doi.org/10.1016/j.cscm.2022.e01460>.
- More, F.M.D.S., Subramanian, S.S., 2022. Impact of fibres on the mechanical and durable behaviour of fibre-reinforced concrete. *Buildings* 12, 1436. <https://doi.org/10.3390/buildings12091436>.
- Morel, J.C., Mesbah, A., Oggero, M., Walker, P., 2001. Building houses with local materials: means to drastically reduce the environmental impact of construction. *Build. Environ.* 36, 1119–1126. [https://doi.org/10.1016/S0360-1323\(00\)00054-8](https://doi.org/10.1016/S0360-1323(00)00054-8).
- Moujoud, Z., Sair, S., Ait Ousaleh, H., Ayouch, I., El Bouari, A., Tanane, O., 2023. Geopolymer composites reinforced with natural Fibers: a review of recent advances in processing and properties. *Construct. Build. Mater.* 388, 131666 <https://doi.org/10.1016/j.conbuildmat.2023.131666>.
- Netinger Grubeša, I., Marković, B., Gojević, A., Brdarić, J., 2018. Effect of hemp fibers on fire resistance of concrete. *Construct. Build. Mater.* 184, 473–484. <https://doi.org/10.1016/j.conbuildmat.2018.07.014>.
- Niu, B., Kim, B.H., 2022. Method for manufacturing corn straw cement-based composite and its physical properties. *Materials* 15, 3199. <https://doi.org/10.3390/ma15093199>.
- Oancea, I., Bujoreanu, C., Budescu, M., Benchea, M., Grădinaru, C.M., 2018. Considerations on sound absorption coefficient of sustainable concrete with different waste replacements. *J. Clean. Prod.* 203, 301–312. <https://doi.org/10.1016/j.jclepro.2018.08.273>.
- Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022. Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ. Chem. Lett.* 21, 741–764. <https://doi.org/10.1007/s10311-022-01532-8>.
- Pachla, E.C., Silva, D.B., Stein, K.J., Marangon, E., Chong, W., 2021. Sustainable application of rice husk and rice straw in cellular concrete composites. *Construct. Build. Mater.* 283, 122770 <https://doi.org/10.1016/j.conbuildmat.2021.122770>.
- Page, J., Khadraoui, F., Boutouil, M., Gomina, M., 2017. Multi-physical properties of a structural concrete incorporating short flax fibers. *Construct. Build. Mater.* 140, 344–353. <https://doi.org/10.1016/j.conbuildmat.2017.02.124>.
- Page, J., Khadraoui, F., Gomina, M., Boutouil, M., 2021. Enhancement of the long-term mechanical performance of flax fiber-reinforced cementitious composites by using alternative binders. *J. Build. Eng.* 40, 102323 <https://doi.org/10.1016/j.jobe.2021.102323>.
- Pandey, J.K., Ahn, S.H., Lee, C.S., Mohanty, A.K., Misra, M., 2010. Recent advances in the application of natural fiber based composites. *Macromol. Mater. Eng.* 295, 975–989. <https://doi.org/10.1002/mame.201000095>.
- Perrot, A., Lecompte, T., Estellé, P., Amziane, S., 2013. Structural build-up of rigid fiber reinforced cement-based materials. *Mater. Struct.* 46, 1561–1568. <https://doi.org/10.1617/s11527-012-9997-9>.
- Phiri, R., Mavinkere Rangappa, S., Siengchin, S., Oladijo, O.P., Dhakal, H.N., 2023. Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: a review. *Advanced Industrial and Engineering Polymer Research* 436–450. <https://doi.org/10.1016/j.aiepr.2023.04.004>.
- Qian, X., Wang, J., Fang, Y., Wang, L., 2018. Carbon dioxide as an admixture for better performance of OPC-based concrete. *J. CO2 Util.* 25, 31–38. <https://doi.org/10.1016/j.jcou.2018.03.007>.
- Rahimi, M., Hissine, O.A., Tagnit-Hamou, A., 2022. Effectiveness of treated flax fibers in improving the early age behavior of high-performance concrete. *J. Build. Eng.* 45, 103448 <https://doi.org/10.1016/j.jobe.2021.103448>.
- Raja, A.K.A., Geethan, K.A.V., Kumar, S.S., Kumar, P.S., 2021. Influence of mechanical attributes, water absorption, heat deflection features and characterization of natural fibers reinforced epoxy hybrid composites for an engineering application. *Fibers Polym.* 22, 3444–3455. <https://doi.org/10.1007/s12221-021-0222-8>.
- Rajendran, M., Bakthavatchalam, K., Leela Bharathi, S., 2023. Review on the hybridized application of natural fiber in the development of geopolymer concrete. *J. Nat. Fibers* 20, 2178578. <https://doi.org/10.1080/15440478.2023.2178578>.
- Rakhsh Mahpour, A., Ventura, H., Ardanuy, M., Rosell, J.R., Claramunt, J., 2023. The effect of fibres and carbonation conditions on the mechanical properties and microstructure of lime/flax composites. *Cement Concr. Compos.* 138, 104981 <https://doi.org/10.1016/j.cemconcomp.2023.104981>.
- Ramesh, M., Deepa, C., Ravanani, A., 2021. In: Jawaid, M., Mavinkere Rangappa, S., Siengchin, S. (Eds.), *Bamboo Fiber Reinforced Concrete Composites*. Springer Singapore, Singapore, pp. 127–145. https://doi.org/10.1007/978-981-15-8489-3_8.
- Ramli, M., Kwan, W.H., Abas, N.F., 2013. Strength and durability of coconut-fiber-reinforced concrete in aggressive environments. *Construct. Build. Mater.* 38, 554–566. <https://doi.org/10.1016/j.conbuildmat.2012.09.002>.
- Reichenbach, S., Preinstorfer, P., Hammerl, M., Kromoser, B., 2021. A review on embedded fiber-reinforced polymer reinforcement in structural concrete in Europe. *Construct. Build. Mater.* 307, 124946 <https://doi.org/10.1016/j.conbuildmat.2021.124946>.
- Rumbayan, R., Sudarno, Ticoalu, A.J.M.W.C., 2019. A study into flexural, compressive and tensile strength of coir-concrete as sustainable building material. *MATEC Web of Conferences* 258, 01011. <https://doi.org/10.1051/mateconf/201925801011>.
- Saad, M., Agwa, I.S., Abdelsalam Abdelsalam, B., Amin, M., 2022. Improving the brittle behavior of high strength concrete using banana and palm leaf sheath fibers. *Mech. Adv. Mater. Struct.* 29, 564–573. <https://doi.org/10.1080/15376494.2020.1780352>.
- Sangadji, S., 2017. Can self-healing mechanism helps concrete structures sustainable? *Procedia Eng.* 171, 238–249. <https://doi.org/10.1016/j.proeng.2017.01.331>.
- Shaikh, F.U.A., Kahlon, N.S., Dogar, A.U.R., 2023. Effect of elevated temperature on the behavior of amorphous metallic fibre-reinforced cement and geopolymer composites. *Fibers* 11, 31. <https://doi.org/10.3390/fib11040031>.
- Shen, Z., Deifalla, A.F., Kaminski, P., Dyczko, A., 2022. Compressive strength evaluation of ultra-high-strength concrete by machine learning. *Materials* 15, 3523. <https://doi.org/10.3390/ma15103523>.
- Sheng, Y., Zhang, B., Yan, Y., Li, H., Chen, Z., Chen, H., 2019. Laboratory investigation on the use of bamboo fiber in asphalt mixtures for enhanced performance. *Arabian J. Sci. Eng.* 44, 4629–4638. <https://doi.org/10.1007/s13369-018-3490-x>.
- Shimamoto, Y., Suzuki, T., 2019. Recycle of rice husk into agro-infrastructure for decreasing carbon dioxide. *Paddy Water Environ.* 17, 555–559. <https://doi.org/10.1007/s10333-019-00752-z>.
- Silva, G., Kim, S., Aguilar, R., Nakamatsu, J., 2020. Natural fibers as reinforcement additives for geopolymers – a review of potential eco-friendly applications to the construction industry. *Sustainable Materials and Technologies* 23, e00132. <https://doi.org/10.1016/j.susmat.2019.e00132>.
- Sinyoung, S., Asavapisit, S., Kunchariyakun, K., 2022. Investigation of bagasse ash as an alternative raw material in clinker production. *J. Mater. Civ. Eng.* 34, 04021433 [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004073](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004073).
- Sithole, N.T., Tsotetsi, N.T., Mashifana, T., Sillanpää, M., 2022. Alternative cleaner production of sustainable concrete from waste foundry sand and slag. *J. Clean. Prod.* 336, 130399 <https://doi.org/10.1016/j.jclepro.2022.130399>.
- Sivakumaresa Chockalingam, L.N., Rymond, N.M., 2022. Strength and durability characteristics of coir, kenaf and polypropylene fibers reinforced high performance concrete. *J. Nat. Fibers* 19, 6692–6700. <https://doi.org/10.1080/15440478.2021.1929656>.
- Sivaranjana, P., Arumugaprabu, V., 2021. A brief review on mechanical and thermal properties of banana fiber based hybrid composites. *SN Appl. Sci.* 3, 176. <https://doi.org/10.1007/s42452-021-04216-0>.
- S.K.K. Singh, S.K., Chourasia, A., 2020. Alternative fine aggregates in production of sustainable concrete- A review. *J. Clean. Prod.* 268, 122089 <https://doi.org/10.1016/j.jclepro.2020.122089>.
- Suhail, M.A., Shrivastava, S., Paritosh, K., Pareek, N., Kovalev, A.A., Kovalev, D.A., Litt, Y.V., Panchenko, V., Bolshev, V., Vivekanand, V., 2022. Advances in applications of cereal crop residues in green concrete technology for environmental sustainability: a review. *Agriculture* 12, 1266. <https://doi.org/10.3390/agriculture12081266>.
- Tayeh, B.A., Alyousef, R., Alabduljabbar, H., Alaskar, A., 2021. Recycling of rice husk waste for a sustainable concrete: a critical review. *J. Clean. Prod.* 312, 127734 <https://doi.org/10.1016/j.jclepro.2021.127734>.
- Thiruchitrambalam, M., Athijayamani, A., Sathiyamurthy, S., Thaheer, A.S.A., 2010. A review on the natural fiber-reinforced polymer composites for the development of roselle fiber-reinforced polyester composite. *J. Nat. Fibers* 7, 307–323. <https://doi.org/10.1080/15440478.2010.529299>.
- Thomas, B.S., 2018. Green concrete partially comprised of rice husk ash as a supplementary cementitious material – a comprehensive review. *Renew. Sustain. Energy Rev.* 82, 3913–3923. <https://doi.org/10.1016/j.rser.2017.10.081>.
- Torkaman, J., Ashori, A., Sadr Momtazi, A., 2014. Using wood fiber waste, rice husk ash, and limestone powder waste as cement replacement materials for lightweight concrete blocks. *Construct. Build. Mater.* 50, 432–436. <https://doi.org/10.1016/j.conbuildmat.2013.09.044>.
- Trabelsi, A., Kammoun, Z., 2020. Mechanical properties and impact resistance of a high-strength lightweight concrete incorporating prickly pear fibres. *Construct. Build. Mater.* 262, 119972 <https://doi.org/10.1016/j.conbuildmat.2020.119972>.
- Van den Heede, P., De Belie, N., 2017. In: Savastano Junior, H., Fiorelli, J., dos Santos, S. F. (Eds.), 9 - Sustainability Assessment of Potentially 'green' Concrete Types Using Life Cycle Assessment. Woodhead Publishing, pp. 235–263. <https://doi.org/10.1016/B978-0-08-102001-2.00010-3>.
- Velandia, D.F., Lynsdale, C.J., Provis, J.L., Ramirez, F., 2018. Effect of mix design inputs, curing and compressive strength on the durability of Na2SO4-activated high volume fly ash concretes. *Cement Concr. Compos.* 91, 11–20. <https://doi.org/10.1016/j.cemconcomp.2018.03.028>.
- Venkateshwar Reddy, P., Saikumar Reddy, R.V., Lakshmana Rao, J., Mohana Krishnudu, D., Rajendra Prasad, P., 2021. An overview on natural fiber reinforced composites for structural and non-structural applications. *Mater. Today: Proc.* 45, 6210–6215. <https://doi.org/10.1016/j.matpr.2020.10.523>.
- Wang, Q., Hussain, A., Farooqi, M.U., Deifalla, A.F., 2022. Artificial intelligence-based estimation of ultra-high-strength concrete's flexural property. *Case Stud. Constr. Mater.* 17, e01243 <https://doi.org/10.1016/j.cscm.2022.e01243>.
- Winarno, S., 2019. Comparative strength and cost of rice husk concrete block. *MATEC Web Conf* 280, 04002. <https://doi.org/10.1051/mateconf/201928004002>.
- Winarno, S., 2021. Preliminary study on hand-cast lightweight concrete block using raw rice husk as aggregate. *IOP Conf. Ser. Earth Environ. Sci.* 933, 012005 <https://doi.org/10.1088/1755-1315/933/1/012005>.
- Wu, H., Shen, A., Cheng, Q., Cai, Y., Ren, G., Pan, H., Deng, S., 2023. A review of recent developments in application of plant fibers as reinforcements in concrete. *J. Clean. Prod.* 419, 138265 <https://doi.org/10.1016/j.jclepro.2023.138265>.
- Xie, X., Zhou, Z., Jiang, M., Xu, X., Wang, Z., Hui, D., 2015. Cellulosic fibers from rice straw and bamboo used as reinforcement of cement-based composites for remarkably improving mechanical properties. *Compos. B Eng.* 78, 153–161. <https://doi.org/10.1016/j.compositesb.2015.03.086>.
- Yang, T., Hu, L., Xiong, X., Petru, M., Noman, M.T., Mishra, R., Militký, J., 2020. Sound absorption properties of natural fibers: a review. *Sustainability* 12, 8477. <https://doi.org/10.3390/su12208477>.
- Yang, M., Chen, L., Msigwa, G., Tang, K.H.D., Yap, P.-S., 2022a. Implications of COVID-19 on global environmental pollution and carbon emissions with strategies for sustainability in the COVID-19 era. *Sci. Total Environ.* 809, 151657 <https://doi.org/10.1016/j.scitotenv.2021.151657>.

- Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022b. Circular economy strategies for combating climate change and other environmental issues. *Environ. Chem. Lett.* 21, 55–80. <https://doi.org/10.1007/s10311-022-01499-6>.
- Yıldırım, H., Özturan, T., 2021. Impact resistance of concrete produced with plain and reinforced cold-bonded fly ash aggregates. *J. Build. Eng.* 42, 102875 <https://doi.org/10.1016/j.jobbe.2021.102875>.
- Yinh, S., Hussain, Q., Joyklad, P., Chaimahawan, P., Rattanapitikon, W., Limkatanyu, S., Pimanmas, A., 2021. Strengthening effect of natural fiber reinforced polymer composites (NFRP) on concrete. *Case Stud. Constr. Mater.* 15, e00653 <https://doi.org/10.1016/j.cscm.2021.e00653>.
- Youssef, A.M., El-Gendy, A., Kamel, S., 2015. Evaluation of corn husk fibers reinforced recycled low density polyethylene composites. *Mater. Chem. Phys.* 152, 26–33. <https://doi.org/10.1016/j.matchemphys.2014.12.004>.
- Yu, X., Sun, L., 2018. Strength, microstructure, and thermal conductivity of the insulation wallboards prepared with rice husk fiber and recycled concrete aggregates. *PLoS One* 13, e0203527. <https://doi.org/10.1371/journal.pone.0203527>.
- Yu, D., Jia, A., Feng, C., Liu, W., Fu, T., Qiu, R., 2021. Preparation and mechanical properties of asphalt mixtures reinforced by modified bamboo fibers. *Construct. Build. Mater.* 286, 122984 <https://doi.org/10.1016/j.conbuildmat.2021.122984>.
- Yusra, A., Triwulan, T., Safriani, M., Ikhsan, M., 2020. Use of bamboo fiber on the relationship between compressive strength and split tensile strength of high strength concrete. *IOP Conf. Ser. Mater. Sci. Eng.* 933, 012010 <https://doi.org/10.1088/1757-899X/933/1/012010>.
- Yuzer, N., Cinar, Z., Aköz, F., Biricik, H., Yalcin Gurkan, Y., Kabay, N., Kizilkanat, A.B., 2013. Influence of raw rice husk addition on structure and properties of concrete. *Construct. Build. Mater.* 44, 54–62. <https://doi.org/10.1016/j.conbuildmat.2013.02.070>.
- Zhang, W., Liu, H., Liu, C., 2022. Impact of rice husk ash on the mechanical characteristics and freeze–thaw resistance of recycled aggregate concrete. *Appl. Sci.* 12 <https://doi.org/10.3390/app122312238>, 12238.
- Zheng, D., Ding, R.-Y., Lei, Z., Xingqun, Z., Chong-Wen, Y., 2015. Thermal properties of flax fiber scoured by different methods. *Therm. Sci.* 19, 939–945. <https://doi.org/10.2298/TSCI130329005Z>.