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Review

Review on the Application of Organic Fibers as Substitutes for Asbestos in Thin Fiber Cement Sheets from a Sri Lankan Perspective

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Abstract: In the past, asbestos siding, roofing, and ceiling sheets became more popular than conventional materials due to their high strength-to-weight ratio, durability, and low cost. However, it was later identified that most types of asbestos are carcinogenic and are responsible for major lethal diseases. In terms of developing a substitute for asbestos, different alternative organic fibers have been investigated as sustainable solutions. Therefore, this article reviewed the usability of organic fibers from wood, banana, bamboo, and coconut coir, which are locally available and abundant in the region, as a substitute for asbestos in the fiber cement industry in Sri Lanka. The quantitative physicomechanical properties of organic fiber and fiber cement composites were evaluated, and the effect of treatment methods on durability was discussed. The previous literature revealed that organic fiber cement thin sheets have comparable mechanical properties in comparison to composites reinforced with asbestos. Furthermore, this study found that these organic-fiber-based composites are energy-efficient and have improved fire resistance. However, the long-term performance is questionable. Hence, further studies on fiber treatment methods and composite durability are needed. Additionally, a comprehensive cost analysis of organic fiber cement composite is recommended to introduce organic fibers into commercial products.

Keywords: organic fiber; asbestos; fiber cement; thin sheets; sustainability; durability

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1. Introduction

Asbestos fiber cement (AFC) composites are extensively used as a building material, mainly in roofing, flooring, and cladding (Figure 1). They are produced using a slurry mixture of ordinary Portland cement (OPC), asbestos fiber, and water in the Hatschek process [1]. AFC is a lightweight material demonstrating a high strength-to-weight ratio [2]. Using AFC composite components in a building reduces dead loads. They increase the aesthetics of the building through their versatile design possibilities, such as textured finishes and a wide range of painting applications [3]. Furthermore, these composites are excessively resistant to fire and termite attacks [2]. Besides the fiber cement (FC) industry, incorporating chrysotile fiber or asbestos in concrete and its effects on the material's properties have been investigated [4]. It has been found that by using crushed chrysotile cement products as a secondary aggregate, compressive strength values of up to 15 MPa can be obtained [4–6]. Furthermore, it has been identified that a concrete incorporating 3 wt% chrysotile as an additive has high strength, frost resistance, low thermal conductivity, low density, and low water absorption [7].

Asbestos is a mineral fiber group comprising six fiber types: chrysotile, amosite, crocidolite, anthophyllite asbestos, actinolite asbestos, and tremolite asbestos [8]. These fibers are categorized into two main groups: amphiboles and serpentine. Chrysotile, also known as white asbestos, exclusively belongs to the serpentine group [8]. Virta [9] noted that 96% of the world's asbestos-based products are made up of chrysotile fiber, which is part of the ongoing debate regarding its carcinogenic properties. Even though some researchers [10] argue that chrysotile does not pose the same level of risk as amphiboles, it was discovered that all kinds of asbestos are carcinogenic and cause severe fatal diseases such as asbestosis, mesothelioma, lung malignancies, and cancer of the larynx [8,11]. Numerous studies have indicated that people exposed to asbestos have a high chance of developing these disorders [12,13]. Consequently, more than 50 countries have banned all forms of asbestos, with many others prohibiting blue and brown asbestos [14]. Hence, global asbestos production has reduced by 40% per year over the last two decades [14].

Figure 1. Asbestos roofing sheets and ceiling sheets.

Before the implementation of restrictions on production and use, the removal of the use of asbestos reinforcement from the FC industry was initiated in the 1970s due to its health hazards [15]. As a replacement, most countries converted most of their Hatschek machines to use wood fibers and synthetic fibers such as polypropylene [2]. Wood fiber is a cellulose fiber extracted from softwood/hardwood and is used to produce FC composites [14]. Moreover, several studies [16–19] have produced durable FC composites with organic fibers extracted from jute, sisal, banana, sugarcane bagasse, bamboo, etc. The generation of these fibers is widely recognized in tropical and equatorial region countries [20]. Despite all these efforts, the consumption of asbestos in Asian countries has risen in recent years due to many commercial activities using asbestos being shifted to developing countries after the ban of asbestos from most developed countries [21]. Moreover, Kazen-Allen [14] ranked Sri Lanka as Asia's eighth-highest asbestos consumer. It is noted that asbestos usage in Sri Lanka was 47,000 tons in 2016. However, it is noted that there are no relevant safety regulations governing the handling, cutting, and drilling of asbestos-containing materials in Sri Lanka [22], and the consequence of this creates high risk levels in the work environment.

Sri Lanka is currently implementing sustainable fiber production and exploring the potential of banning asbestos [23]. As stated by Udawattha et al. [24], standard specifications still need to be met by alternative FC products, limiting the potential to replace asbestos in roofing sheets. Therefore, it is imperative to research sustainable fiber materials that are suitable for FC manufacturing.

This article presents an overview of sustainable substitutes for asbestos fibers from different organic fibers using a comprehensive literature review. Fiber production availability, treatment, and the properties of wood, banana, bamboo, and coconut coir fiber are discussed since these fibers are locally available and abundant in the region [20]. Subsequently, a quantitative assessment of the properties of FC composites based on the above-mentioned organic fibers is evaluated, and the effect of treatment methods on durability is discussed. Finally, potential research is proposed to realize the application of organic fibers as substitutes for asbestos in thin FC sheets.

2. Different Types of Organic Fibers

Cellulose is a widely available organic material primarily sourced from wood and also present in various plant fibers like banana, coir, bamboo, etc. Its structure consists of a linear chain of two anhydroglucose molecules covalently bonded through an oxygen atom, with repeating units of 10,000 to 15,000 times [19,25,26]. As shown in Figure 2, hydrogen bonds and van der Waals forces between adjacent glucose molecules stabilize the chain, forming microfibrils that eventually aggregate into cellulose fibers [26,27].

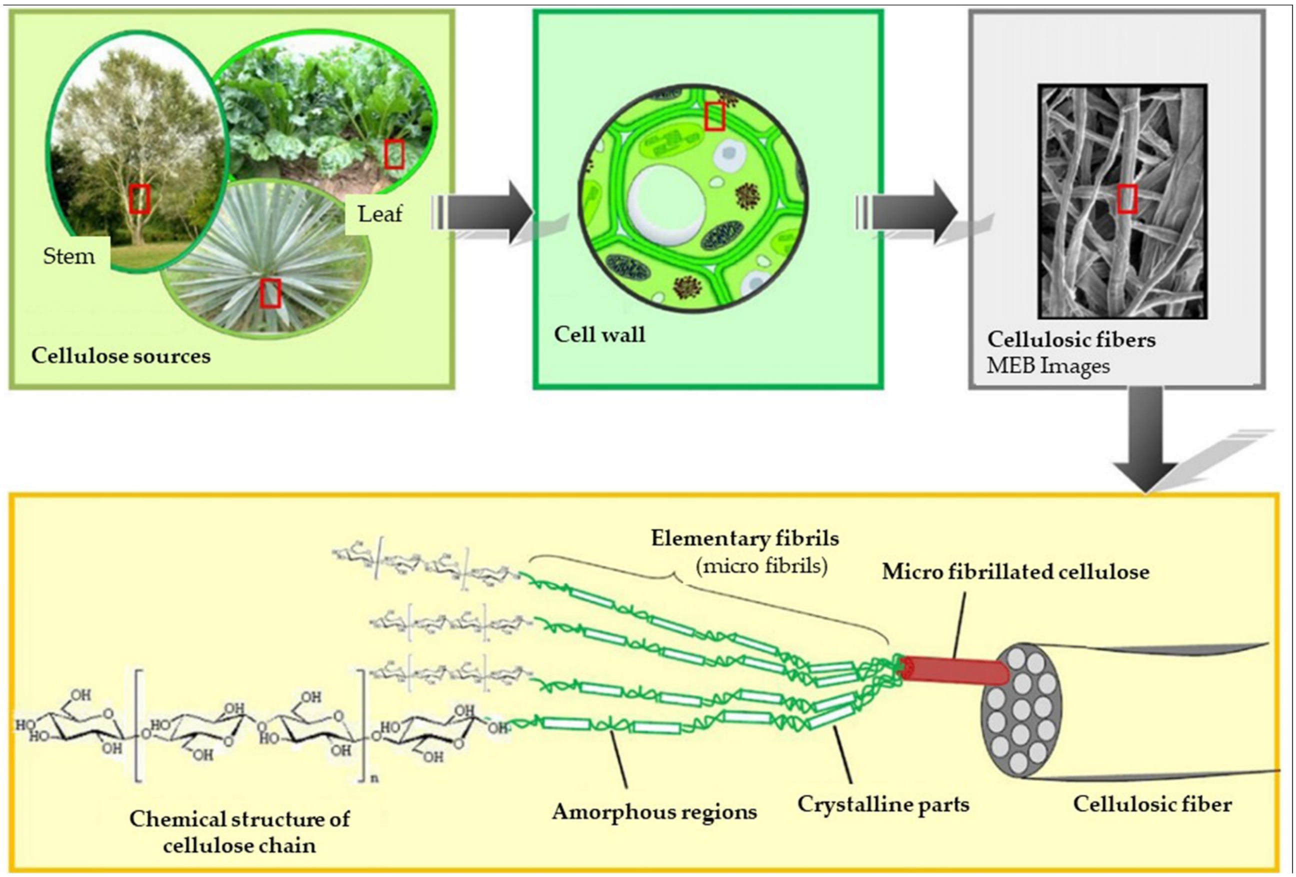

Figure 2. Diagrammatic representation of the structure of cellulose fibers: from sources to molecules [26].

This structure provides excellent mechanical properties, making organic fiber an attractive, sustainable material for various construction applications. The oldest application of organic fibers used in building materials to enhance strength and bonding and reduce cracking was found in sunbaked bricks that were produced approximately 3500 years ago [28]. In medieval times, organic fibers such as wood and straw fibers were used to increase the volume stability of mortars [29]. Over time, different organic fibers have been included in cementitious compounds. Following numerous improvements, cellulose-fiber-based FC composites are now widely used for nonstructural components of residential construction [15]. Sri Lanka is a tropical country full of organic fibers with excessive properties. Therefore, this section illustrates the usability of readily available organic fibers in Sri Lanka for the FC industry.

2.1. Fiber Availability and Production

Using wood fibers as reinforcement in cement sheets has successfully changed the FC industry [2]. Since it has been found that softwood (*Pinus radiata*) has higher strength than hardwood (*Eucalyptus regnans*) fibers in FC composites, researchers have focused more on the development of softwood (*Pinus radiata*) fibers [30]. In Sri Lanka, the Forest Department planted 23,000 hectares (230 × 10^6 m^2) of pine trees (mainly *Pinus caribaea*) between 1953 and 1983 to overcome the timber shortage [31]. These plantations are retained as forests, impacting wildlife and hydrology [32]. Therefore, these woods can be used to produce organic fibers.

Banana fibers are obtained from the stem of the banana plant (*Musa sapientum*). Nearly 60,000 hectares (600 × 10^6 m^2) of land are used for banana farming in Sri Lanka. In a hectare, around 3000–5000 plants are cultivated [33]. After harvesting, most of these plants are disposed of as waste [20]. This agricultural waste can be utilized to produce fibers. Using recycled agricultural waste materials in buildings is a reliable option for attaining sustainability. Furthermore, banana fibers have a high resistance to seawater and are used to strengthen marine structures [34].

Bamboo comprises lignocellulosic-based organic fibers and resembles a perennial grass in nature. It is generally found in the native vegetation of many tropical and subtropical locations worldwide, and the world's bamboo fiber production is estimated to be about 30 million tons per year [35]. Bamboo has drawn the attention of scientists and engineers for use as reinforcement in cementitious composites due to its durability and high availability.

Most tropical nations currently produce raw coconut fibers for a low price, and that fiber can be treated using simple techniques. 250,000 tons of coir fiber is produced globally [34]. According to Rohit and Dixit [34], India and Sri Lanka export coir fibers at a proportion of almost 90% of the total global production. Those fibers are still used in traditional coir products such as brushes, ropes, and mats [34]. Hence, many researchers focus on applying coconut coir fiber to reinforce FC composite to produce low-cost building materials, especially for developing countries.

2.2. Fiber Treatment

Chemical treatments can improve the strength and cleanliness of organic fibers. Such treatments enhance wettability, remove impurities, and increase the strength of fibers, leading to better performance. Chemical treatments can enhance the adhesion between the fibers and matrix, which improves strength and durability [36]. Organic fiber treatments proposed in different studies are listed in Table 1.

The pulping process—which can be based on chemical (kraft process) treatment, the thermomechanical process (TMP), or a mix of the two—reflects the characteristics of the cellulose pulp fibers extracted from wood [37]. Campbell and Coutts [37] investigated the effect of the pulping method on the strength of wood fibers. It was noted that cellulose pulp fibers produced using the kraft process have 300% higher tensile strength than those from the TMP. Moreover, it was identified that the treated wood fiber outperformed untreated fiber in certain chemical treatments and fiber–cement combinations [38]. Pehanich et al. [38] noted that 0.25–0.75% silane treatment resulted in the highest modulus of rupture (MOR) values for kraft fiber–cement specimens. However, treated newspaper fiber–cement composites showed the highest average modulus of elasticity (MOE) values with N silicate treatments. It was noticed that the effectiveness of the treatments varied depending on the fiber type [38].

Jagadeesh et al. [39] identified that alkali-treated banana fibers have 100% higher tensile strength than untreated fibers. Increased surface roughness from alkali treatment improves mechanical bonding and reduces water absorption in banana fibers [39]. Furthermore, a 5% concentration of sodium hydroxide was applied by Akinyemi et al. [40] to treat the surface of banana fibers, resulting in reduced cellulose and lignin content and improved surface roughness for enhanced bonding with the matrix. Using a microstructural analysis, it was noticed that the banana fibers exhibited calcium silicate hydrate (C-S-H) encapsulation, bridging the gap between the fiber and cement matrix. Moreover, the alkaline treatment caused the surface of the banana fiber to become hollow and rough, indicating a reduction in cellulose and lignin. This roughened surface facilitated the filling of cement hydrate products, leading to optimal strength compared to other treatments [40].

Bamboo fibers that have been microwave-assisted treated with sodium hydroxide and hot-water-treated were used by Akinyemi et al. [41] to reinforce cement composites. As a result of enhanced interfacial adhesion between the cement matrix and the bamboo fibers, a 10% concentration of sodium hydroxide was adequate to improve the tensile strength compared to other trial treatments. Furthermore, the glycerol-modified bamboo-fiber-reinforced cement composites showed considerably better flexural strength and a lower amount of drying shrinkage than aluminate-ester-modified bamboo fibers [42]. Onyekewere et al. [43] noted that acetylation treatment significantly reduced the water absorption of bamboo fibers, with up to a 151% reduction, making it more effective than other treatment methods. Additionally, Sheng et al. [44] identified that a 0.2% potassium permanganate treatment improved elongation at flexural deformation, and composites with treated bamboo fibers exhibited remarkable water resistance capabilities.

As pretreatment for coir fibers, it was discovered that boiling in water for 2 h was enough to remove water-soluble compounds such as sugar [45]. According to that study, Asasutjarit et al. [45] observed that washed and boiled coir fiber had a large amount of lignin. Therefore, boiled and cleaned coir fiber is stiffer. Similarly, Moura et al. [46] noted that the hot-water TMP is preferred for coconut coir fiber due to its mild nature and absence of aggressive solvents or chemicals. Furthermore, the study conducted by Arsyad et al. [47] revealed that 20% sodium hydroxide treatment increased the tensile stress of coconut fiber, while potassium permanganate treatment decreased it. However, it was found that both sodium hydroxide and potassium permanganate treatments improved the compatibility between the coconut fiber and the matrix. Furthermore, Brigida et al. [48] concluded that hydrogen peroxide treatment is suitable for removing undesirable waxes and fatty acids on the fiber surface. Moreover, many researchers have treated coir fibers with alkali, potassium permanganate, and fiber hybridization to upgrade the fiber properties [49].

Among these treatment methods, 5–10% alkali treatment can be identified as a more productive method for enhancing fiber–matrix adhesion and dimension stability. However, the effectiveness of the treatments varied depending on the fiber type. The effect of these treatments on durability is discussed in the later part of this article.

Table 1. Proposed treatment methods for the selected organic fibers.

Fiber Type	Treatment Method	References
Wood	Acetylation	[50]
	Thermomechanical treatment	[37]
	Alkali treatment	[51]
	Fiber hybridization	[52]
	Silane treatment	[38]
Banana	Hot-water immersion	[53]
	Alkali treatment	[39,40]
	Fiber hybridization	[54]
Bamboo	Acetylation	[43]
	Alkali treatment	[41]
	Modified by glycerol	[42]
	Permanganate treatment	[44,55]
	Hot-water immersion	[41]
Coconut coir	Hot-water immersion	[45,46]
	Alkali treatment	[47,56]
	Permanganate treatment	[47]
	Fiber hybridization	[57]
	Peroxide treatment	[48]

2.3. Physicomechanical Properties of Organic Fibers

In order to measure the tensile strength of a single organic fiber, a microtensile test is conducted [58]. It is performed using a modern microtensile tester or a universal tensile machine (Figure 3) following ASTM D3822 [59] and ASTM C1557 [60] requirements nowadays [61,62]. The cross-section of the fibers for tensile strength calculations is measured using an optical microscope [63]. Since the irregularity of the cross-section along the organic fiber will give inaccurate properties with a high standard deviation, Hu et al. [61] developed an improved tensile testing method with two approaches: fiber selection and cross-section area determination.

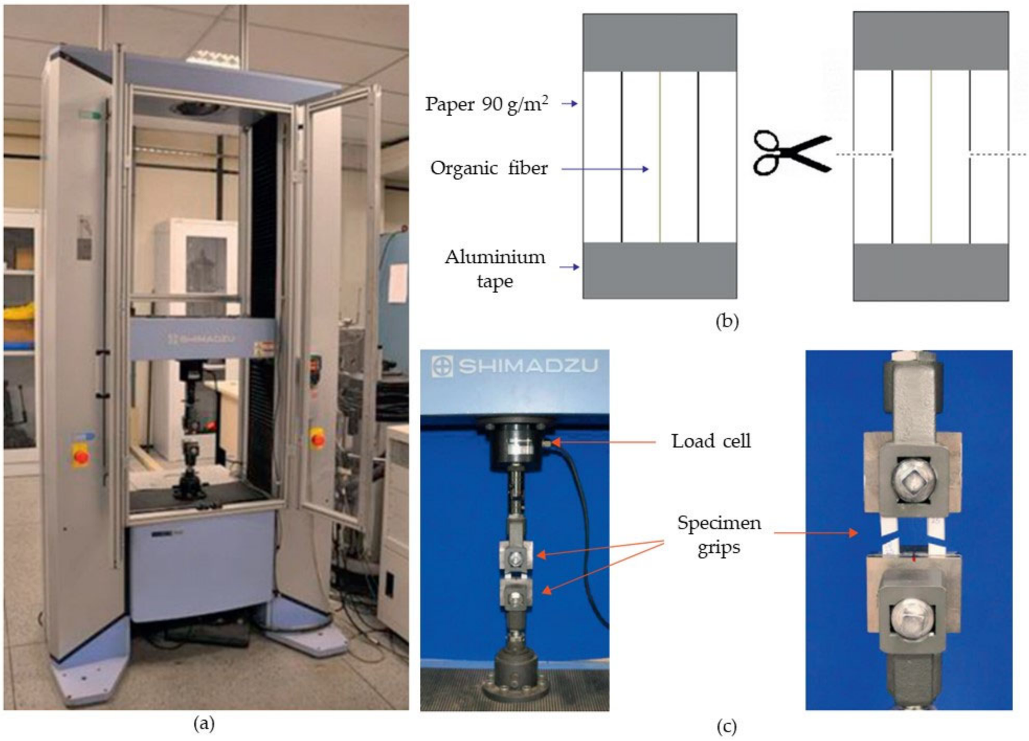

Figure 3. Tensile testing of single organic fiber, (**a**) universal tensile machine, (**b**) sample preparation, and (**c**) clamp details [62].

Similarly, in the research conducted by Aveston [64], the tensile strength of chrysotile fibers with a length of 3 mm was evaluated using an "Instron" testing machine. The testing procedure involved gluing the fibers with "Araldite" to the flat' centers cut in the ends of a pair of 4.8 mm diameter brass rods. These rods were aligned in a jig at the desired gauge length. After the glue had set, the rods were inserted into special mountings on the "Instron" machine and secured in place with set screws. Finally, the jig was removed, and the tensile strength of the chrysotile fiber was determined using a cross-section head speed of 0.1 mm/min [64].

Campbell and Coutts [37] measured kraft wood fibers with a cylindrical shape with tapered ends exhibiting a length-to-diameter ratio ranging from 50 to 60, and it was found that the tensile strength was between 500 and 1000 MPa. Moreover, banana fiber has length properties (2.7–5.5 mm) and a tensile strength of 600 MPa, almost similar to wood fibers [65]. Similarly, Xie et al. [66] utilized bamboo cellulosic fibers with a length ranging from 2.1 to 2.9 mm and a diameter ranging from 8.5 to 17.7 mm. Additionally, Chen et al. [67] measured the tensile strength of chemically and mechanically isolated 20 mm length bamboo fiber strips gripped with wood slices. It was noted that the tensile strength of the chemically isolated bamboo fibers could reach 600 MPa [67]. A coconut coir fiber is typically around 350 mm in length, with a diameter ranging from 0.12 to 0.25 mm, and it has a density of approximately 1250 kg/m^3 [68]. Other than that, with the ability to withstand 4–6 times greater strain than other fibers, coconut coir fibers have the highest toughness of any known organic fiber [69] since it is known for having a high amount of lignin coating [68].

The mechanical properties of the discussed organic fibers are listed in Table 2. Chrysotile fiber has a greater tensile strength and modulus than the discussed organic fibers. However, using different fiber content and fiber lengths, the required properties can be developed in FC composites [28].

Table 2. Physicomechanical properties of organic fibers compared to chrysotile.

Fiber Type	Critical Fiber Length (mm)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Elongation to Break (%)	References
Chrysotile fiber	1.0–5.0	3060–4480	160	-	[28]
Wood (*pinus radiata*)	2.0–4.5	500–1000	7–70	0.5–1.4	[28,37]
Banana	2.7–5.5	600	17–18	3	[65,70,71]
Bamboo	2.1–2.9	540–630	11–17	2	[66,67,71]
Coconut coir	5.0–10.0	94–159	1.2–1.8	20–67	[63,68,69]

3. Fiber Cement Composites

3.1. Composite Production

It was found that the fiber distribution in the FC composite affects its physical and mechanical characteristics, and fiber dispersion depends on the production method [72]. The key goals in the production process include ensuring a homogeneous dispersion of fibers within the matrix, enabling a strong interaction between the cement matrix and fibers to facilitate fiber pull-out, minimizing porosity in the matrix, and optimizing the fiber content to strike a balance between reinforcement and maintaining matrix continuity [73]. Manufacturing FC thin sheets on a large scale typically employs the Hatschek process using a combination of OPC, fibers, and water [74]. However, the production of FC composites in the Hatschek process has been modified by various researchers [73], and alternative materials have been used. For instance, they use sand or supplementary cementitious materials to substitute a portion of the OPC in the composite [20,75–78].

Numerous studies [20,65,77–81] have utilized the slurry vacuum dewatering technique to incorporate pulp fibers into the cement matrix, resulting in composites with randomly dispersed fibers (8 wt%). This was achieved by mixing the matrix materials with the appropriate amount of fiber in water to form a slurry of 20 wt% solids, which was then transferred to a drilled mold and subjected to vacuum pressure [77]. Subsequently, the board was pressed until it reached a desirable thickness of 6 to 15 mm [77,78]. A similar production process was also reported by Soroushian et al. [82].

Andeniji et al. [83] used the casting methodology to prepare 6 mm thick fiber-reinforced cement composites with coconut fibers using a conventional vibration table. The composite was vibrated for 60 s to minimize porosity, and no pressure or vacuum was used. It was identified that a similar production process was followed by Toledo-Filho et al. [84].

Furthermore, fiber cement mortars were prepared by Mohr et al. [85] using a mixing process that involved combining fibers, fine aggregate, and water without a vacuum or pressing. The fibers and fine aggregate were stirred with 50% water to separate the fibers and achieve uniform dispersion. Subsequently, cement was added, followed by the remaining water [85]. In another study by Mohr et al. [86], a kraft pulp softwood FC composite was produced with a similar method after fibers were treated with cationic starch and fly ash for enhanced dispersion during mixing.

In contrast to the randomly dispersed methods, in Silva et al.'s [87] study, fibers were washed, cut into 400 mm sections, and arranged into five layers with a volume fraction of 10% to produce aligned FC composites. This method used cotton fibers to stitch the layers and ensure even spacing. A mortar matrix was created with a mix ratio of 1:1:0.4 for cementitious material, sand, and water. The mixture was placed layer by layer in a steel mold, alternating with aligned fibers, and consolidated through vibration. Test specimens were prepared with dimensions of 400 mm $\times$ 50 mm $\times$ 12 mm, compressed, and cured for 24 h in the mold [64,87,88].

3.2. Mechanical Performance

Universal testing machines were used to conduct the three-point loading test described in different standards for flat and corrugated sheets [20,23,76,89]. Twenty-four hours of immersion in water for the FC specimen was followed by testing. Based on the tests, the MOR, MOE, and fracture toughness were identified using Equations (1)–(3), respectively. The fracture energy was determined by integrating the load–deflection curve to the point corresponding to a 50% reduction in load-bearing capacity [20].

$$\mathrm{MOR} = 3pl/2bd^2 \quad (1)$$

$$\mathrm{MOE} = ml^3/4bd^3 \quad (2)$$

$$\text{Fracture toughness} = \text{fracture energy}/bd \quad (3)$$

Coutts [30] identified that an FC composite with 8 wt% cellulose fiber from softwood (*Pinus radiata*) has a higher tensile strength than an FC composite with the same percentage of hardwood (*Eucalyptus regnans*). Consequently, high-performance cellulose fibers were developed using softwood kraft pulp [28]. The autoclaved cellulose FC composite produced using these fibers became more popular after the ban on asbestos in many countries [2]. Kraft softwood pulp is added with an ideal fiber percentage of 8% by weight, and half of the rest is replaced by silica flour instead of using 92% from the OPC [75]. Autoclaved curing became the standard method due to the ability of rapid production, as the curing process can be finished within two days, while conventional air curing takes 28 days to gain strength [75].

Zhu et al. [90] investigated the mechanical properties of different contents of banana fiber. According to that study, the elastic modulus decreased from 14 GPa to around 6 GPa when the fiber content increased from 2 to 16% by mass, and it was also noted that the composites with a fiber content within the range of 10% to 16% had a steady flexural strength around 24 MPa [90]. Savastano et al. [81] investigated the flexural strength of banana-fiber-reinforced cement composites with 96% of OPC at 28 days. It was noted that the flexural strength could reach up to 15.5 MPa at a fiber loading of 4% by mass. Moreover, in previous research by Savastano et al. [20], it was discovered that the addition of 12% by weight of waste fiber pulp to cement composites granted a flexural strength of over 20 MPa (Figure 4).

According to Correia et al.'s [79] study investigating the physical–mechanical behavior of composites reinforced with 8%-mass-based bamboo organosolv pulp, this FC composite had a flexural strength of more than 7 MPa. Xie et al. [66] found the optimal bamboo fiber content to be 12 wt%, while adding fibers up to 16 wt% led to an 8.9% reduction in flexural strength. It can be described by the observed fiber agglomeration induced by higher fiber content. Fiber agglomeration leads to decreased flexural strength, as discussed by Chakraborty et al. [91]. Furthermore, according to various research works on short bamboo fibers and their composites, introducing short bamboo fiber as a reinforcing material may vastly improve the tensile strength of composites [71].

Paramasivam et al. [92] developed FC corrugated sheets using coir fibers. They used a fiber length of 2.5 cm, a volume fraction of 3%, and a casting pressure of 0.15 MPa to create the FC corrugated sheets with higher strength and improved aesthetics. After a 28-day hydration period, Asasutjarit et al. [45] examined the mechanical characteristics of a lightweight FC board made from coconut coir fibers, focusing on parameters such as fiber length, coir pretreatment, and material ratio. The researchers in [45] discovered that utilizing boiled and washed fibers with a length of 6 cm produced superior outcomes for the best fiber loading of 33% with a water/cement ratio of 1. It was identified that an FC sheet could be produced with a flexural strength of 19.94 MPa; however, water absorption is around 20%. The study observed a proportional increase in moisture content, thickness swelling, and water absorption with the rise in the coconut coir ratio in the mixture [45]. The increase in water absorption can be attributed to the inherent hygroscopic nature of organic fibers. These fibers tend to absorb and retain water, resulting in an overall increase in the water absorption of the composite as the fiber content increases [28]. Relatively more extensive fiber loading might affect the durability properties, and consequently, Lertwattanaruk and Suntijitto [68] developed a thin sheet using OPC and limestone powder as a binder with a binder/sand ratio of 1:1. It was noted that the optimized fiber content of 2.5% binder resulted in a flexural strength of 10.18 MPa and 4.67% water absorption. Also, it was noticed that with increasing fiber content, the flexural strength decreased and the water absorption increased.

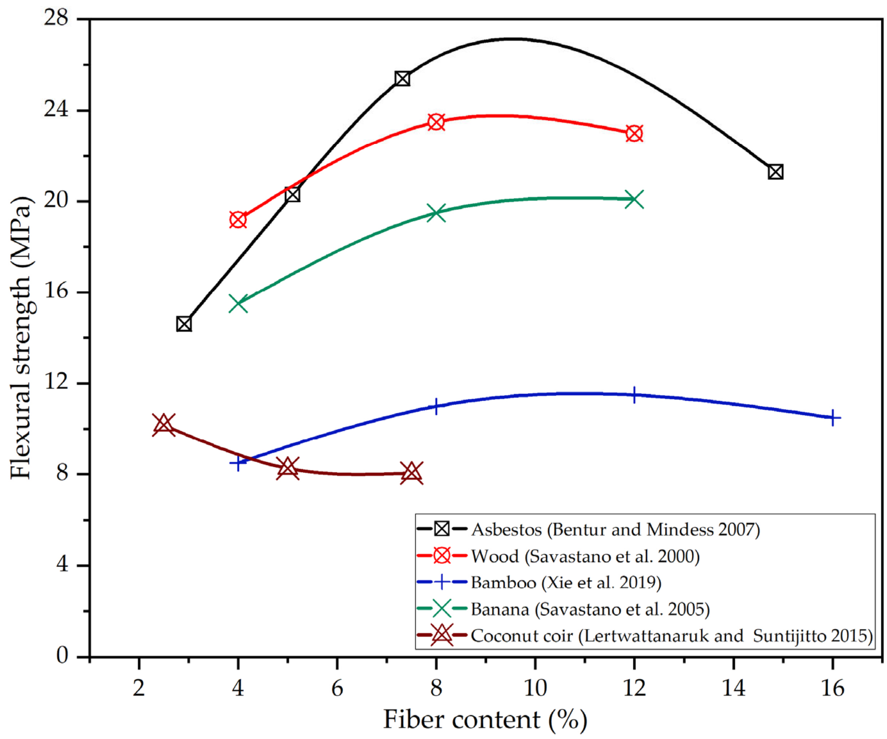

Figure 4. Flexural strength of FC composites with different fiber content [20,28,66,68,80].

Moreover, in Sri Lanka, a coir fiber corrugated sheet with a raw material OPC/fly ash/sand/fiber weight ratio of 12:2:1:5 was studied by Peiris and Weerasinghe [23], and the corresponding FC sheet did not satisfy the breaking load limit according to ISO 10904:2011 [93]. Similarly, De Silva et al. [76] tested an FC corrugated sheet with 250 g of coir fibers for 7.5 kg of cement, which complied with Sri Lanka Standards Institution SLS 9–2: 2001 [94]. Although the identified breaking load was 4.73 kN/m, which should be greater than 5 kN/m, the researchers suggested microfibers with different fiber contents to increase the flexural strength [76].

The mechanical properties of FC composites with optimal fiber content are presented in Table 3. It is illustrated that the discussed organic FC composites have considerable flexural strength comparable to asbestos FC sheets. However, the flexural strength of FC thin sheets should be checked with the limitations of the given code of practice. According to the Sri Lanka Standards Institution SLS 9–1:2001 [95], flexural strength should not be less than 16 MPa for the loading perpendicular fiber direction of the flat sheet. It should be noted that the identified flexural strength of the bamboo and coconut coir FC composite is lower than the SLS standards. Apart from the mechanical properties of the composite, physical properties such as moisture movement and water absorption should comply with the limits described in the standards for FC flat sheets and corrugated sheets according to their application.

Table 3. Physicomechanical properties of organic FC compared to AFC in definite ratios.

Fiber	Fiber Content (*w*/*w*) (%)	Density (kg/m^3)	Flexural Strength (MPa)	Modulus of Elasticity (MPa)	Fracture Toughness (kJ/m^2)	References
Chrysotile fiber	8	2100	25.4	14.73	-	[28]
Softwood	8	1540	23.5	10.3	1.32	[20]
Banana	12	1580	20.1	7.04	1.01	[20,81]
Bamboo	12	-	11.5	-	2.20	[66]
Coconut coir	2.5	1250	10.18	-	-	[68,76]

3.3. Durability Performance

Due to changes in moisture conditions, the matrix is extremely susceptible to volume changes in thin FC components, where the cement concentration is typically high. Other than that, hygroscopic organic fibers may worsen this situation as the fibers change volume due to swelling and contracting [28]. The shrinkage strains can be above 0.15%, and these dimensional changes are higher than those seen in normal concrete. The component's shapes are distorted as a result of this shrinking. Fortunately, these changes do not lead to a loss in strength [28].

Due to environmental exposure, organic-fiber-based FC composites are vulnerable to reduced physical and mechanical properties. Bentur and Mindess [28] discussed the long-term performance of such composites and identified that fiber degradation due to alkaline attacks and biological attack is a major drawback. The alkalinity effect on the fibers and the consequent loss of strength when organic fibers that are exposed to an alkaline medium are used in cement composites were clearly illustrated by Ramakrishna and Sundararajan [56]. Moreover, Wei and Meyer [96] studied organic cellulose fiber degradation in an alkaline and mineral-rich environment, typical of cementitious matrices. This involved incorporating sisal fibers into OPC pastes to evaluate the degradation of fibers with metakaolin cement replacements. Lignin and pectin were the first components to degrade, followed by hemicellulose, which decreased the cell walls' integrity, as shown in Figure 5. The amorphous regions of cellulose nanofibrils degraded, forming cellulose nanocrystals, while the crystalline regions remained stable. A slight pH reduction in the matrix pores mitigated the organic fibers' degradation. Although fibers with metakaolin showed an 8.6% increase in performance after 5 wetting and drying cycles, after 15 and 30 cycles, the tensile strength dropped by 4.8% and 19.4%, respectively [96].

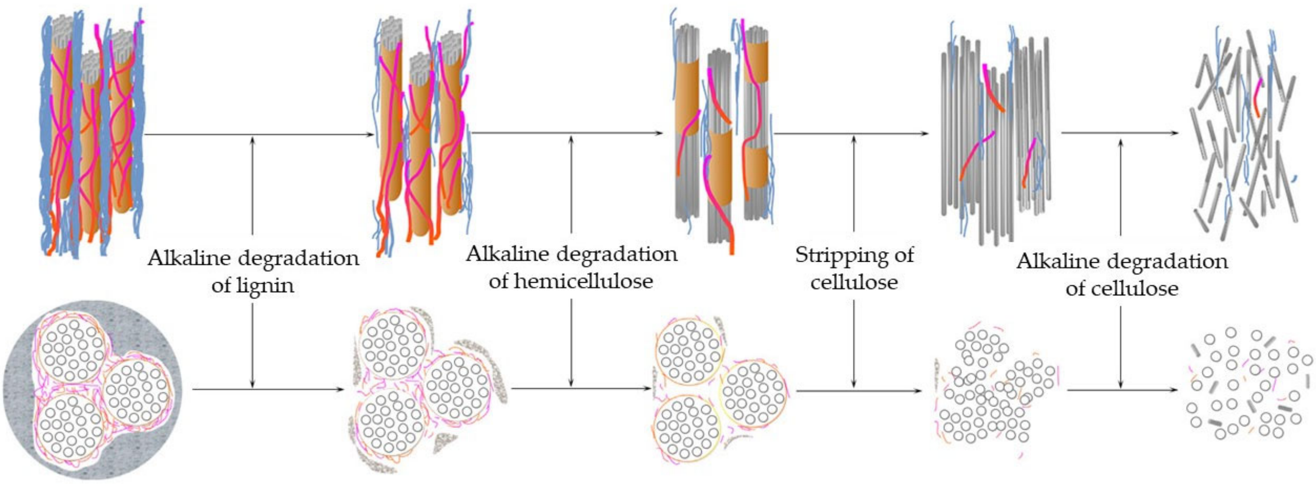

Figure 5. Visual illustration of alkaline-induced degradation process in organic fibers [96].

In-depth research was conducted to prevent bamboo fiber deterioration in high-alkalinity conditions. Cement that contains minerals can be used in its place to lower the alkalinity of the solution and improve the durability of organic-FC-based composites [97]. By reducing the alkalinity of the pore solution through cementitious material optimization using metakaolin and montmorillonite, the performance of organic-fiber-reinforced cement mortar can be improved [70]. Baghban and Mahjoub [98] reviewed the addition of supplementary cementitious materials (SCMs) in the cement matrix, which increased the durability of organic fibers. It was demonstrated that adding SCMs as a replacement for cement protects lignocellulosic fibers against chemical degradation by reducing the alkalinity of the matrix [98].

It is well known that the pretreatment of organic fibers can increase their resistance to deterioration by adding protection cover to the fiber's surface or upgrading the cellulose structure. Cooke [99] illustrated that the autoclaved method develops cellulose FC composites' durability and mechanical characteristics. Additionally, different studies have been carried out to enhance the durability properties using pretreatment methods such as silane coating, alkaline treatment, sodium silicate, and potassium silicate treatment [98]. It is noteworthy that the alkali treatment of fibers enhances their surface properties and improves adhesion with the matrix. On the other hand, if untreated fibers are added to a matrix with alkaline conditions, the hydrated products may not bond effectively with the fibers, resulting in reduced strength and performance for the composite material.

3.4. Energy Performance

The energy performance of building envelopes, such as siding, roofing, and ceilings, is critical in maintaining indoor thermal comfort and air quality while reducing energy consumption. These components are integral to the overall energy efficiency of a building, providing insulation, mitigating air infiltration, and reflecting or absorbing thermal energy [100]. The material selection of siding, roofing, and ceilings has a significant impact on their energy performance, as the abilities of these materials to reflect solar radiation, retain heat, and provide insulation are critical parameters [101]. Implementing energy-efficient building envelopes through material selection and proper installation can result in substantial energy savings, lower utility costs, and improved indoor environmental quality [93]. Multiple studies in the literature [41,68,92,100–103] have shown that incorporating organic fibers into composite materials reduces thermal conductivity and weight reduction. The organic fibers act as an efficient insulating layer, lowering the composite's total heat transfer qualities.

Compared to traditional masonry blocks, Gheni et al. [100] discovered that employing 10.8 wt% white oak wood fibers and 64.2 wt% fly ash in the construction of eco-friendly masonry blocks resulted in a 64% decrease in energy consumption and a 77.2% decrease in thermal conductivity. Bentchikon et al. [104] conducted a test to identify the thermal conductivity of cement paste reinforced with different fiber content using the parallel hot-wire method. It was identified that the thermal conductivity of the cement paste drastically decreased when adding 4% cellulose fibers. Furthermore, Dirisu et al. [105] conducted a study investigating the thermal conductivity of various ceiling tiles using waste materials. The study results showed that the ceiling tiles made from pine fiber had the lowest thermal conductivity value among all the materials tested.

Taiwo et al. [106] utilized Lee's disk apparatus to determine the thermal conductivity of composite materials. The results of the study showed that the composite incorporating 20% banana fiber had a thermal conductivity of 0.111 W/m K. It is important to highlight that this value represents a significant decrease in thermal conductivity compared to traditional asbestos cement materials (0.967 W/m K) [107], indicating the potential for banana fiber as a reinforcement material in the development of energy-efficient composites.

Singh et al. [108] investigated the thermal and acoustic characteristics of cement fiberboard manufactured from bamboo fibers in detail. The cement fiberboard building offered good thermal insulation from April to May, with an outdoor temperature of 45 °C and an internal temperature of 30 °C, according to the study data. The thermal transmittance, or the rate of heat transmission through a building material, was reported to be between 1.9 and 2.5 W/m^2 K for the cement fiberboard structures [108].

Ali [109] reviewed coir-fiber-reinforced cement boards with lower thermal conductivity and acoustic properties than traditional asbestos sheets. Moreover, the PCA-Zamboanga Research Center in the Philippines developed a coir FC board consisting of 30% to 40% coir fiber and 60% to 70% cement by weight. The resulting material exhibited low thermal conductivity (0.9 W/m K) and demonstrated favorable results in flame and smoke emission tests, displaying a slow burning rate and low smoke emission [110].

3.5. Fire Resistance

Fire protection and fire safety in buildings are crucial aspects of contemporary construction engineering. The use of proper building materials is critical to ensure fire protection and safety. Cementitious composites, such as siding boards, ceilings, and roofing sheets, are widely used building materials that provide fire protection and improve building safety [106]. Historically, asbestos fibers were utilized as reinforcement materials in these composites due to their fireproof properties [2]. In particular, asbestos fibers were known to prevent the development of smoke in the event of a fire [111]. However, due to asbestos reduction, there has been a growing interest in using organic fibers as reinforcement materials in cement composites with fireproof properties. Numerous studies [112–115] have investigated the fire performance of organic-fiber-reinforced cement sheets. These studies evaluated the fire resistance and mechanical properties of cement composites reinforced with different organic fibers (such as wood, bamboo, banana, and coir fibers) after a fire event.

In a study by Thongcharoen et al. [115], structural insulated panels covered with wood fiber–cement board specimens were tested for fire performance using the UL94 Horizontal/Vertical Flame Chamber [115]. The specimens, measuring 12 mm × 125 mm × 10 mm, were tested according to the ASTM D3801-10 [116] standard. The study results showed that the fiber–cement board had good fire performance ratings, with no self-ignition observed during testing.

Schabowicz et al. [114] assessed the destruction of a cellulose FC board subjected to fire. The researchers employed a three-point bending test in combination with the acoustic emission method to evaluate the sample's behavior under fire conditions. It was found that the fire temperatures, ranging from 500 °C to 700 °C, significantly impacted the structural integrity of the FC boards. The modulus of rupture, a measure of the strength of samples, decreased by up to 0.22 MPa in response to the fire exposure. Moreover, the researchers also concluded that a high temperature damaged the cellulose fibers contained in the board. Similarly, Bugno et al. [112] measured the strength of fiber–cement board using the acoustic emission method while the samples were exposed to direct fire to heat the material to 400 °C. The study found that the specimens exposed to fire and high temperatures had the largest decrease in strength.

4. Sustainability and Cost Analysis

Organic fibers as reinforcement materials in building materials have received increased attention in recent years due to their potential to contribute to the construction industry's sustainability [80]. According to previous studies [117–119], it has been reported that the use of these organic fibers can significantly improve the mechanical properties, dimensional stability, and durability of building materials, while also reducing the environmental impact of traditional synthetic or asbestos fiber reinforcement extraction, processing, and disposal. In addition, using these fibers can promote the utilization of waste or by-product materials, such as wood chips, banana stems, bamboo culms, and coconut husks, that would otherwise be discarded as waste [40]. Cement fiberboard shows high thermal insulation properties, reducing energy consumption and costs and decreasing carbon emissions [119]. Research and development in this field can support the growth of green building materials and promote using locally sourced materials for sustainable construction.

The market price of a 50 kg bag of chrysotile asbestos is reported to be USD 30.52 [120]. On the other hand, the price of cellulose fiber derived from wood pulp is lower, at USD 24.41 per 50 kg bag [121]. The market price for coconut coir fiber has been reported to be around USD 14.04 per 50 kg bag [122], although additional charges may be incurred for the necessary fiber treatment processes. Since banana fiber is extracted from agricultural waste and bamboo fibers are readily available, the production cost of these fibers mainly consists of the treatment process. However, more research needs to be conducted on the cost analysis of these fibers for the FC industry. Despite the higher price of available banana and bamboo fibers for the textile industry [123], the potential cost advantage of these fibers for the FC industry remains to be determined. It should be studied in future research efforts. However, Suriani et al. [124] presented the cost of banana fiber and bamboo fiber as USD 44.5 and USD 25 per 50 kg, respectively, as quoted from the study of Ho et al. [125]. However, further studies are needed to evaluate the cost-effectiveness of employing organic fibers in producing FC composites, even though these fibers have high potential as a sustainable material for general application.

5. Summary and Future Works

This article reviewed the usability of organic fibers extracted from wood, banana, bamboo, and coconut coir as a substitute for asbestos in the FC industry in Sri Lanka. In light of organic fibers being readily available locally, renewable, relatively inexpensive, and not carcinogenic, such a substitution is extremely vital. Similarly, organic fibers can easily be applied in the existing Hatschek process to produce FC products. The review was conducted within the thematic areas of fiber treatment, availability, the mechanical properties of fibers and FC composites, and long-term performance. In addition, fire resistance, energy performance, and sustainability were also discussed. The findings of the conducted study are as follows:

i. It was found that, among treatment methods, alkali treatment can be identified as a more productive method for enhancing fiber–matrix adhesion and dimension stability. However, the effectiveness of the treatments varied depending on the fiber type.
ii. Even though chrysotile fibers have a greater tensile strength (3060–4480 MPa) than organic fibers (under 1000 MPa), organic FC composites can be developed to carry high strength using different fiber lengths and contents. Moreover, except for bamboo and coconut coir, the flexural strength of the discussed FC composites was 20.1–23.5 MPa, which satisfies the SLS 9–1:2001 requirement.
iii. It is noteworthy that existing research needs more information to implement a durable FC product.
iv. The review found that organic FC composites can provide fire resistance comparable to asbestos-reinforced composites. Furthermore, using organic fibers in cement composites can provide similar benefits, such as enhanced thermal insulation (thermal conductivity, 0.1–0.9 W/m K) and improved energy efficiency.
v. Using organic fibers in building materials can also help to ensure the industry's sustainability by lowering the environmental impact of building material manufacturing and disposal.
vi. Cellulose fibers are utilized in the FC industry, with wood fiber and coconut fiber being less expensive than chrysotile asbestos fiber. Banana and bamboo fibers, extracted from agricultural waste and fast-growing trees, have limited cost analysis for their use in the FC industry.

The current review spectrum on using organic fibers in thin-sheet production within the FC industry must be revised to support practical implementations. To fully realize the potential advantages of using organic fibers, the following investigations into their use in FC thin-sheet production are recommended.

i. The durability of organic fibers is a pressing concern, as the organic nature of plant fibers combined with the alkaline composition of cementitious composites presents challenges. To address this issue, more effective pretreatment methods with minimal environmental impact must be explored to improve the use of organic fibers in FC thin sheets.

ii. In addition to exploring the durability of organic fibers, a life cycle assessment (LCA) of the development of organic-fiber-reinforced composites would promote their long-term sustainability.

iii. Moreover, limited cost analyses for using organic fibers in the FC industry currently exist, making further studies necessary to determine their cost-effectiveness.

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