sustainability

MDPI

Review

A Comprehensive Review on Construction Applications and Life Cycle Sustainability of Natural Fiber Biocomposites

Hammad Ahmad, Gyan Chhipi-Shrestha, Kasun Hewage and Rehan Sadiq *

Life Cycle Management Lab, School of Engineering, University of British Columbia (Okanagan Campus), 1137 Alumni Avenue, Kelowna, BC V1V 1V7, Canada

* Correspondence: rehan.sadiq@ubc.ca

Abstract: The construction industry is continuously searching for sustainable materials to combat the rapid depletion of global resources and ongoing ecological crises. Biocomposites have recently received global attention in various industries due to their renewability, low cost, and biodegradability. Biocomposites' potential as a sustainable substitute in construction can be understood by identifying their diverse applications. Moreover, examining their life cycle environmental and economic impacts is important. Therefore, this study is a novel attempt to encompass biocomposites' construction applications and their environmental life cycle performance. Statistical analysis is done related to the temporal distribution of papers, publishers, literature type and regions of studies. First, this paper reviews the latest research on the applications of natural fiber biocomposites in construction with their key findings. The applications include fiber reinforcements in concrete, external strengthening elements, internally filled hollow tubes, wood replacement boards, insulation, and non-structural members. The second part covers the life cycle assessment (LCA) and cost studies on biocomposites. The life cycle studies are currently rare and require more case-specific assessments; however, they highlight the benefits of biocomposites in cost savings and environmental protection. Finally, this study provides key suggestions for increasing the applicability of biocomposites as sustainable construction materials.

Keywords: biocomposites; construction material; life cycle assessment; natural fibers; sustainable construction; life cycle cost

check for updates

Citation: Ahmad, H.; Chhipi-Shrestha, G.; Hewage, K.; Sadiq, R. A Comprehensive Review on Construction Applications and Life Cycle Sustainability of Natural Fiber Biocomposites. *Sustainability* **2022**, *14*, 15905. https://doi.org/10.3390/su142315905

Academic Editor: Jonathan Oti

Received: 26 August 2022
Accepted: 23 November 2022
Published: 29 November 2022

1. Introduction

The global population (currently 7.7 Billion) has grown rapidly in recent times and is expected to reach 9.7 Billion by 2050 [1]. This rise in the world population has resulted in increased urbanization worldwide, requiring more buildings and housing. As of June 2020, the global construction industry invests approximately 12 trillion dollars annually [2], which mainly comprises single and multiple residential buildings. The ecological degradation and environmental crises worldwide have driven the research focus on sustainability to incorporate environmental conservation, economic, social, and health impacts in decision-making [3,4]. Industrial and social innovations are an immediate need for conserving natural resources and protecting the environment.

The building materials have changed over the years ranging from straw, wattle, daub, clay, and stones in ancient times to innovative engineered materials like composites and variants of concrete in recent years [5]. Despite the widespread benefits of the construction industry and its benefits to the economy, the building sector is considered to be one of the major contributors to several problems, including greenhouse gas emissions, construction and demolition (C&D) waste, high energy consumption, socio-economic impacts, and other environmental emissions [6–8]. Moreover, the construction phase and its activities are not the only sources of environmental loads. The studies on the life cycle of the current construction materials have enlightened that many impacts are associated with other life stages of those materials [9].

The environmental impacts can be attributed to several building materials, construction activities and phases, e.g., the production of one-ton cement (with potential use in buildings) releases one ton of carbon dioxide (CO_2) into the air [10]. Moreover, heavy and sophisticated equipment used for construction activities requires substantial amounts of energy. Similarly, the growing construction and demolition (C&D) wastes pose another issue, making it more important to protect the environment through recycling and waste management [11]. The United States and Canada produce 500 million tonnes and 33 million tonnes C&D debris, most of which goes to landfills [12]. Therefore, the research in civil and material engineering is continuously focusing on and investigating the materials that can provide the same or better performance as conventional materials with reduced environmental and economic impacts. Although conventional materials such as concrete, timber, and steel hold a major share in global construction projects, natural fibers and their derivatives have made inroads in various forms in the building sector.

Biocomposites are composite materials containing renewable constituents either as fiber reinforcement or as a polymer in matrix form. Biocomposites have been studied and used internationally recently due to their attractive characteristics like bio-degradability, abundant availability, low cost, less energy requirements, and environmental health benefits [13]. Although biocomposites have been widely used in the automotive industry due to their light weight, biocomposites have also shown the potential to replace typical building materials. Their field applications are limited; however, they have been studied extensively in research arenas.

Few recent articles review natural fiber use in cementitious composites [14–17]. Nonetheless, these articles primarily deal with only one application, i.e., cementitious composites in construction. The discussions are directed towards the factors impacting the chemical and mechanical properties of fibers and cementitious matrix rather than their suitability as construction material. There are numerous other applications of biocomposites which include externally applied fiber reinforced polymer (FRP) [18], internally filled FRP tube [19], bio-based sandwich panels [20] and insulation, among others. Consequently, there is a need to assemble the information available in the literature to examine all applications in construction in terms of their benefits and drawbacks. Moreover, only mechanical performance may not be sufficient to provide a clear picture to the policymakers and regulators regarding the use of biocomposites in the building sector. Economic costs and environmental impacts throughout biocomposites' life cycle must be studied rigorously.

Most published research on biocomposites in the building sector has focused on mechanical properties. Limited research has been conducted to date on the life cycle impacts of biocomposites in terms of environmental and economic performance [21]. This fact is further augmented by a low number of available records on engineering databases while searching for the life cycle sustainability of biocomposites. Although biocomposites seem to be "green" or sustainable by definition, it is necessary to ensure environmental impacts are minimized after accounting for all life cycle stages rather than by transferring impacts from one to another life cycle stage. For example, an environmentally friendly material imported from a distant region might be less sustainable in its life cycle due to large fuel consumption and emissions during its transport. Therefore, it is important to scrutinize the current status of life cycle studies on biocomposites.

This paper aims to fill the above-mentioned research gaps. The methodology section describes the review process and statistical analysis of the literature. The subsequent section briefly introduces biocomposites, natural fibers and their classification with industrial applications. Section 4 provides an account of construction applications of natural fibers biocomposites in the building sector with key findings, concerns and challenges. This synthesized information will help better understand biocomposites' potential in the construction market. Section 5 analyzes the current status of life cycle studies to understand the sustainability of these materials. The assembled information on construction applications in connection with the life cycle impacts of biocomposites can be valuable for planners, engineers, and policymakers in the field of sustainable infrastructure development for countries rich in agricultural feedstock like Canada. Moreover, it will provide insight into job opportunities for the people dependent on agriculture and forestry.

2. Methodology

Various natural fiber biocomposites have been studied and implemented in the construction sector globally. These biocomposites differ in aspects like type of fibers, content, mix ratio, and type of polymer (matrix), among other characteristics. Therefore, this review was restricted to biocomposites based on natural fibers. Natural fibers have three origins: plant, animal, and mineral. In the 1970s, asbestos (which belongs to the mineral category) was banned in many countries due to its health challenges [22]. Later, asbestos was identified as hazardous and was associated with many health concerns and risks [23]. Similarly, the fibers from animal sources have been scarcely explored in literature [24,25]. Consequently, natural fiber composites based on plants/lignocellulosic fibers have been of primary interest and covered in this review.

The review methodology and process were divided into two phases. Phase 1 was dedicated to searching articles on the applications of natural fiber biocomposites in the construction industry. For this purpose, a combination of keywords for natural fibers and their applications in buildings was used. The keywords for the search included "biocomposites", "buildings", "construction", "natural fibers", "natural composites", "FRP" and "concrete" on two internet databases, including Compendex Engineering Village and ScienceDirect. Furthermore, the useful references of the screened research papers and Mendeley/Google Scholar resources augmented the search for additional papers. ScienceDirect was selected being the mainstream database, whereas Compendex Engineering Village provides results relevant to engineering. The papers not conforming to the scope of this review were excluded. A similar approach was used in Phase 2, where the search focused on life cycle assessment and life cycle costing of the biocomposites in construction applications. The combined number of articles retrieved from each database (Figure 1) was 141. Engineering village and ScienceDirect contributed with 56 and 11 exclusive articles, respectively, and 74 were present in both databases. Other 34 articles were used to augment the review.

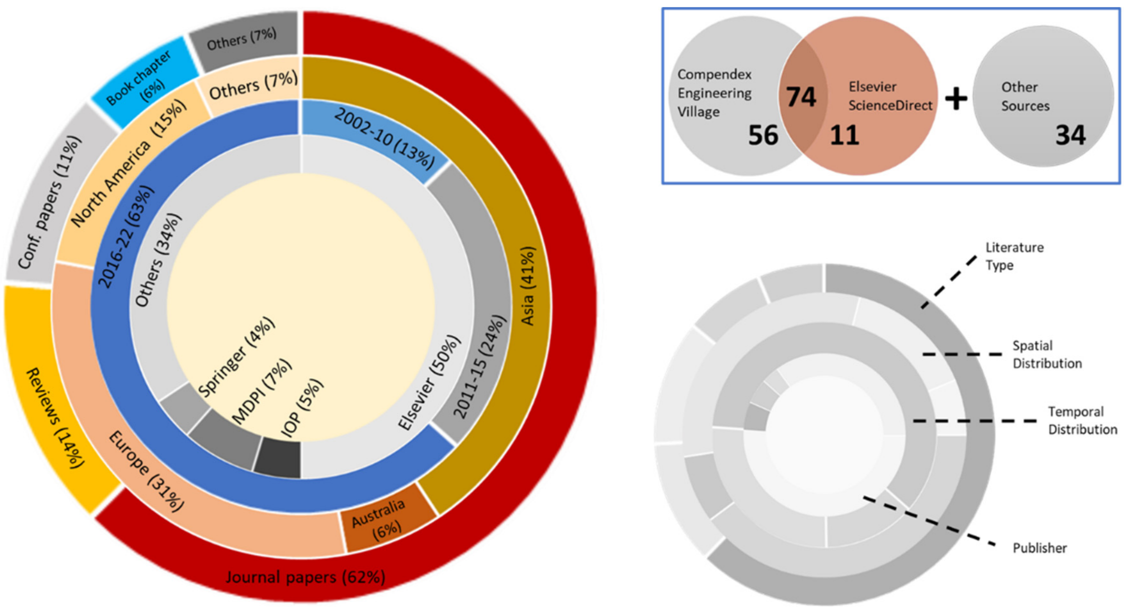

Figure 1. Statistical analysis of reviewed literature.

The statistical analysis of the reviewed literature is presented in Figure 1. More than half of the literature covered in this article has been published by Elsevier, whereas 27 articles came from IOP, MDPI, and Springer. The remaining articles belong to various publishers, including ASCE, Taylor & Francis, and Wiley. Literature-wise, 108 referred papers (62%) are journal articles ranging from experimental studies to numerical analysis, followed by 24 review articles and 19 conference papers. The other sources of literature include book chapters and reports. Moreover, the temporal distribution of the literature has been divided into three segments. The first timeframe from 2002–2010 comprises 22 references (13%). Most of these have been the source of preliminary information and pioneer studies on biocomposites. The second (2011–2015) and third segments (2016–2022) contribute 24% and 63% of the reviewed papers, demonstrating the rise in biocomposite studies in the last five years. In the context of spatial distribution, the research from Asian countries has been cited the most (71 times), followed by Europe (53 times) and North America (26). Many countries in Asia depend on their agriculture and have explored natural fibers and biocomposites extensively. Further details on the spatial and temporal distribution can also be observed in the tables of subsequent sections.

3. Biocomposites

Natural materials and their derivatives have served humankind since ancient times; however, the industrial revolution in the last century replaced them with synthetic materials [26]. Nevertheless, the current global problems have shifted the trend towards natural materials with biocomposites. It is essential to distinguish among terminologies occasionally used interchangeably when describing biocomposites. The term "biocomposite", as the name indicates, is a composite material that contains at least one natural ingredient [26,27]. This terminology encompasses several materials and therefore provides the flexibility to tailor the materials according to the needs. If all the components in a biocomposite are from natural/renewable sources, it is called a green composite. In other words, bio-based (green) biocomposites have both matrix and reinforcement based on biomass. Conversely, if any of the biocomposite components come from non-renewable/petroleum-based sources, it is referred to as partly eco-friendly biocomposite [13]. Figure 2a provides a sketch to distinguish between green and partly eco-friendly biocomposites.

The next term covered under biocomposites is "Biopolymer", defined as a material that possesses constituents (units) partially or entirely derived from biomass, e.g., polyphenolic polymer. The difference between a natural polymer and a biopolymer is that the former is naturally made, whereas a biopolymer made by repeatedly integrating the monomer (unit) can be a synthetic (artificial) material. Therefore, natural polymers can be classified as a sub-category of bio-polymers [13,21].

Several types of polymers exist, and some of them are naturally degradable. Environmentally degradable polymers belong to a diverse group of sources from synthetic and renewable sources [28], and they can be called biocomposites depending on the presence of natural constituents. A comprehensive classification of environmentally degradable polymers is given in Figure 2c. The holistic sustainability of a biocomposite depends on its life cycle performance [17,20]. In other words, a sustainable biocomposite is a product of renewable/recycled resources having energy and cost-effective manufacturing. Moreover, its life cycle stage constituents must have minimum environmental impacts. This paper covers only plant-based natural fiber biocomposites, which can be termed as a subset of biocomposites.

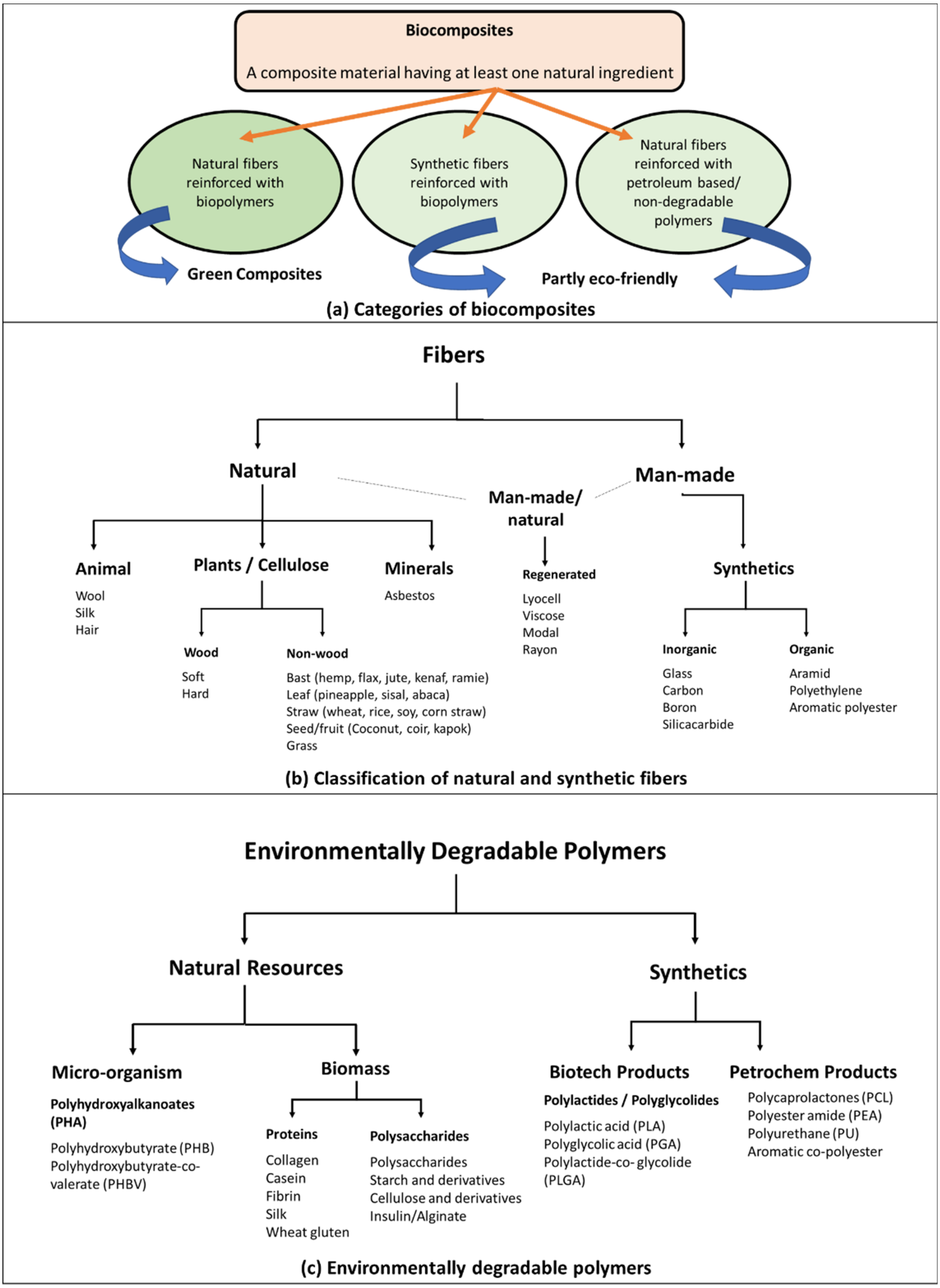

Figure 2. (**a**) Biocomposite and its types (**b**) classification of natural and synthetic fibers (**c**) classification of environmentally degradable polymers [13,27–31].

3.1. Natural Fibers for Biocomposites

Due to the sustainability concerns of plastics and related polymers, natural materials have undergone marked improvements over the last few years as they have been incorporated into biocomposites [32]. Moreover, renewable feedstock-based composites' production is expected to rise from 5% (2004) to 25% in 2030 in the United States [33]. The use of these fibers to make biocomposites is a result of their structural properties, abundant availability, low cost, and depletion of petroleum-based composites [34]. Natural fibers can be distinguished based on their origin, as they can be obtained from plants, animals, and mineral sources [35]. The classification of natural fibers based on their origin are presented in Figure 2b. The fibers which have found their applications in the composite industries belong to the plant/vegetation category, which are often elaborated under the heading of cellulose fibers as well [13,27–29]. These plant fibers can be associated to two sources: (i) agriculture and (ii) post-processing production residue of crops [36]. Fibers including hemp, flax, jute, and sisal have established industrial production lines, whereas the other fibers in this category need improved production practices to streamline commercial success [37]. Furthermore, Table 1 provides the subject fibers' annual production (2020) and producer countries.

Table 1. Natural fibers annual production and producing countries [38,39].

Natural Fiber	Production (Metric Tons)	Main Producers
Cotton	26,120,000	China, USA, India, Pakistan
Kapok	96,000	Indonesia
Jute, kenaf and allied fibers	2,500,000	India, Bangladesh, China, Thailand
Flax	310,000	China, France, Belgium, Belarus, Ukraine
Hemp	70,000	China
Ramie	-	China
Abaca	83,000	Philippines, Ecuador
Sisal, henequen & allied fibers	210,000	Brazil, China, Tanzania, Kenya
Coir	970,000	India, Sri Lanka

3.2. Rise in Research and Industrial Applications

Biocomposites have been continuously growing in research and development due to their benefits despite the stronghold of plastics and petroleum-based composites over global markets during the last century. Figure 3 illustrates the data fetched from two large databases: "Compendex Engineering Village" and "Elsevier ScienceDirect". The first published research dates back to 1981 at Compendex and 1984 in ScienceDirect; however, there has been a significant increase in biocomposite research in the last decade. This rise can be attributed to the search for sustainable solutions for modern-day climatic problems.

Biocomposites have made their mark with industrial applications and have replaced synthetic composites in many applications [40]. The most abundant use of biocomposites has been observed in the automotive industry [41–44]; several other applications are listed below.

- Construction materials and building components (interior and exterior) [19,45,46]
- Furniture components and boards [47,48]
- Sound absorbers for noise control [49]
- Mats, gardening articles, and storage cabinets [47]
- Packaging materials for electronics, foods and other products [50–52]
- Biomedical and optical applications [53]
- Dentures, tissue engineering, medical implants and 3d-printed joints [54–56]
- Marine application (limited) [57]

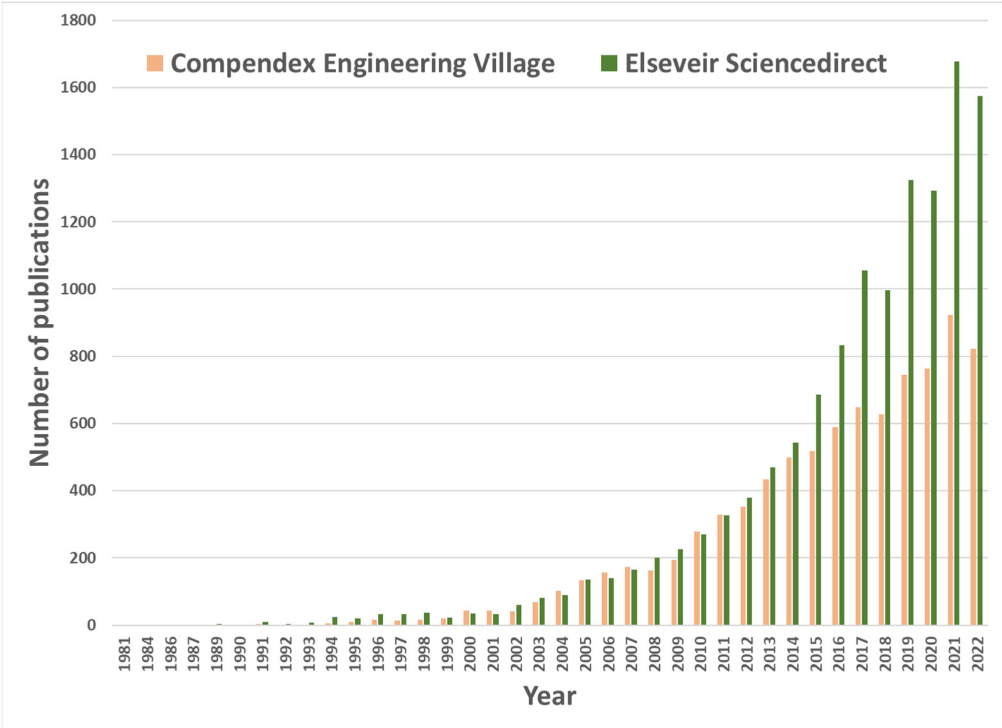

Figure 3. Research progress in biocomposites.

The next sections will focus on the biocomposites' use as construction materials.

4. Biocomposites as Construction Materials

Conventional building materials have enormous environmental implications, which have encouraged using natural materials for environment-friendly buildings with lesser impacts [58]. This sub-section discusses the applications of natural fibers biocomposites used in the building sector or may have a potential application.

4.1. Field Applications

Globally, researchers have investigated the potential of natural fiber biocomposites mainly on experimental setups. Nonetheless, there have been some ground-breaking illustrations of their usage in real-time structural applications as well, which are discussed. In 2016–2017, Dutch researchers developed the "first bio-based bridge" at Eindhoven University of Technology [59]. The 14 m long pedestrian bridge comprised hemp and flax fibers combined with polylactic acid core to carry a load of 500 kg/m^2. Moreover, the contributing researcher claimed it to be competent evidence of bio-based construction materials' load-bearing capacity.

Similarly, another recent innovation in Friesland Province of Netherlands saw the opening of a bicycle swing bridge "Ritsumasyl", based on flax biocomposites [60]. The bridge was constructed in line with the European Union's mission towards making Europe "the first climate-neutral continent" by the mid of the 21st century. The bridge was primarily constructed using flax reinforced epoxy; nevertheless, steel was still used in machinery, hinges, gears, and motors. Furthermore, the bridge with 20 m decks and 1.2 m I-beams support was designed to carry 5000 kg. The disadvantages of flax composites included more sagging (40 cm compared to 5 cm with glass) and a higher coefficient of expansion. Still, a lifting mechanism catered for the sagging, and the expansion coefficients were closer to metals. The advantages included creep stopping after a certain time interval, more service life than actual designed life, recycling and re-use potential, opportunities for farmers, affordability, and sustainability.

Another important application explored practically and documented in comprehensive review articles is hempcrete or lime-hemp concrete [61–63]. Hempcrete, a mix of hemp fiber, lime and water, has been mainly used as wall, roof, sub-slab and window insulation [63] due to its light weight and low thermal conductivity [61]. Moreover, it can also repair old stone and lime structures. The compressive strength is 5–10% of ordinary concrete; however, it shows reasonable ductility and durability [62,63]. Lightweight hemp lime bricks and hemp clay bricks (load bearing) are among the market materials. The use of hemp fiber in ordinary concrete has been covered in the subsequent section.

4.2. Natural Fibers as Reinforcement

Concrete itself as a construction material is brittle, necessitating reinforcement having an adequate bond with the concrete to enhance its ductility. Steel rebars have been used for years to counter concrete's inherent brittleness. Moreover, synthetic fibers like glass and steel have been used to improve concrete's post-cracking behavior. Similarly, natural fibers have been adopted, especially in the last decade, to investigate their impacts on concrete's mechanical properties. A round-up of these applications has been provided in Table 2.

Table 2. Use of natural fibers as reinforcement.

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
			Flax		
Fernandez (2002) [64]	USA	Flax fiber reinforced concrete	Promote the use of flax fiber as a sustainable material	Enhanced strength and toughness	Recommended for shear strengthening for potential material savings
Page et al. (2017) [65]	France	Flax fiber reinforced concrete	Improvement of fresh state implementation conditions. Improve the mechanical properties in the hardened state	Compressive strength decreased with an increase in fiber content but flexural capacity was enhanced	Reduction in concrete workability due to fibers and increased air content.
Kouta et al. (2020) [66]	France	Flax fiber reinforced earth concrete	Investigate fracture behavior of flax fiber in earth concrete	Flax fibers augmented the fracture properties of earth concrete (increased with % and length of fibers) and provided ductility (by crack bridging)	Can be used as a sustainable option for earthen concrete but need more exploration in terms of damage mechanism.
Benmahiddine et al. (2020) [67]	France	Flax shive reinforced concrete	Investigate the potential of flax concrete towards sustainable construction	Flax concrete having 14.5% bulk concrete provided the maximum strength. The strength values were lower as compared to conventional concrete (and decreased with more flax content)	Recommended by authors to be used as insulation/filling materials
Garikapati and Sadeghian (2020) [68]	Canada	Flax-lime concrete blocks with jute reinforcement	Study flax shives with lime-based binder as a construction material with jute mesh	Enhanced energy absorption and bending capacity using jute mesh	Recommended as masonry blocks and insulation in wall cavities
Rahimi et al. (2022) [69]	Canada	Treated flax fibers in high-performance concrete	Comparing treated flax fiber with light weight aggregates and admixtures for controlling shrinkage of high-performance concrete	12% increase in compressive strength by flax fiber Flax fibers caused 23–26% reduction in shrinkage while improving the energy absorption capacity of concrete	Treated flax fiber recommended for better volumetric stability of high-performance concrete

Table 2. *Cont.*

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
			Hemp		
Li et al. (2006) [70]	Australia	Hemp fiber reinforced concrete	Experimental investigation for mechanical properties of hemp fiber concrete	Fiber content is crucial in mechanical performance Compressive strength reduces by adding fibers in comparison to conventional concrete The wet mix shows better flexural performance as compared to the dry mix	Recommended for pavements
Brujin et al. (2009) [71]	Sweden	Hemp-lime concrete	Feasibility study of hemp lime concrete as a load-bearing member	Low compressive strengths and young modulus	Not suitable for load-bearing application
Arnaud and Gourlay (2012) [72]	France	Hemp fiber reinforced concrete	Study the impact of various mix design factors on hemp concrete	Hemp concrete's properties depend on curing conditions, age, binder type/content and hemp characteristics	Care to be exercised during mix design
Awwad et al. (2012) [73]	Lebanon	Hemp fiber reinforced concrete	Investigate the mechanical and thermal properties of hemp fiber concrete	Fibers addition resulted in coarse aggregate reduction No impact on tensile strength and increased ductility Reduction in thermal conductivity and modulus of elasticity	Hemp fibers reduced the compressive strength by about 25% (0.75–1% fibers); therefore, recommended for non-structural applications
Awwad et al. (2013) [74]	Lebanon	Hemp concrete masonry blocks (untreated hemp and hurds)	Investigating the behavior of hemp fibers masonry blocks Reducing the aggregates and density of blocks while enhancing thermal and acoustic properties	Compressive strength decreased with an increase in hemp fiber content About 20% decrease in thermal conductivity	Fulfils minimum strength requirement for non-load bearing members
Merta and Tschegg (2013) [75]	Austria	Natural fibers in concrete	Study the influence of fibers on energy absorption capacity of concrete	70%, 2% and 5% increase in fracture energy using hemp, straw and grass fibers respectively in comparison to unreinforced concrete	4%, 7% and 8% decline in split tensile strength with hemp, straw and grass, respectively
Walker et al. (2014) [76]	Ireland	Hemp-lime concrete	Evaluate the post-exposure performance of hemp-lime concrete against sodium chloride	Resistance to biodeterioration (hemp concrete)	Recommended as a sustainable material
Zhou et al. (2016) [77]	London, UK	Hemp fiber reinforced concrete panels	Investigate the impact resistance with other mechanical properties	Low compressive strength but high split tensile strength with longer fibers (20 mm) as compared to short (10 mm) Better impact resistance, low crack propagation, and high energy absorption with longer fibers (20 mm)	No comparison with unreinforced concrete It can be used for structures subjected to impact loading with careful selection of fiber length and content

Table 2. *Cont.*

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Barbuta et al. (2017) [78]	Romania	Natural fibers in polymer concrete with fly ash	Analyze the behavior of hemp/wool on the mechanical properties of polymer concrete	Decline in compressive strength but increase in tensile strength (for wool only) Greater flexural strength with hemp fibers in comparison to wool Increase in fiber dosage decreased the density	Suggested for eco-friendly concrete with enhanced thermal performance
Grubesa et al. (2018) [79]	Croatia	Hemp fiber reinforced concrete	Study the influence of fiber treatment on their properties at ambient temperature and fire resistance of hemp concrete	Hemp fibers did not impact the fire resistance of concrete. Crack propagation was reduced at elevated temperature (400 °C)	Not useful for fire resistance under very high temperatures but useful for enhancing fire resistance at moderately high temperatures
Bamboo					
Wong et al. (2010) [80]	Malaysia	Fiber reinforced polyester concrete	Point out the optimum volume fraction % and fiber length for improved impact resistance	16.6 times higher toughness was achieved using optimum content under study (50% fiber volume fraction and 10 mm fiber length	Durability for outdoor applications may be a drawback that can be explored and improved
Zhang et al. (2013) [81]	Shanghai, China	Bamboo fiber reinforced concrete	Study the mechanical performance of bamboo fiber concrete	Positive impact on split tensile strength but adverse impact on compressive strength	Maybe used for controlling initial micro-cracking.
Ahmad et al. (2014) [82]		Bamboo reinforced concrete beam (fibers)	Study the effect of bamboo fiber on mechanical properties of concrete	No influence on 28 days strength but high 50-day strength Increased flexural strength and modulus of elasticity	Recommended for low-cost buildings
Agarwal et al. (2014) [83]	India	Bamboo reinforced beam and column	Improve the bond strength at the interface of bamboo fiber concrete and other mechanical properties	Bonding strength of treated bamboo depends on the adhesive used Untreated bamboo does not impact strength Treated bamboo (8%) provides the same strength as steel (0.89%) Flexural load capacity increased by 29% by 1.49% treated bamboo	Suggested as potential substitute reinforcement
Moroz et al. (2014) [84]	Canada	Bamboo reinforced concrete masonry shear walls	Compare bamboo to steel as a replacement in shear walls	Increased shear capacity and ductility vs. unreinforced masonry Reasonably closer behavior to steel reinforcement	Waterproofing of bamboo reinforcement is required Long-term properties investigation and cost analysis should be done
Goh and Zulkornain (2019) [85]	Malaysia	Bamboo fiber reinforced concrete	Investigate the influence of various fiber fractions on the compressive strength of concrete	Improved compressive strength was achieved with 0.5% fibers (optimum) Beams with only bamboo fiber had lower strengths as compared to control concrete	Suggested by authors for either non-structural applications or in flexure with supporting shear strengthening
Sridhar et al. (2022) [86]	Turkey	Treated jute and bamboo fiber in reinforced concrete	Comparison of the effectiveness of chemically treated jute and bamboo fiber on reinforced concrete's mechanical properties	Optimal dosage was 1.5% and 2% for bamboo and jute, respectively Improved compressive and flexural strengths by both fibers (17–31%) Scanning electron microscopy showed good bonding between fiber and matrix	Treated bamboo recommended for concrete flexural capacity enhancement

Table 2. *Cont.*

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Coconut (coir)					
Dhandhania and Sawant (2014) [87]	India	Coir fiber reinforced concrete	Study coconut fiber as replacement reinforcement for roofs	Reasonable strength enhancement No corrosion and cooling ability due to low thermal conductivity	Can be used to avoid corrosion
Ahmad et al. (2020) [88]	Pakistan	Coconut fiber reinforced high-strength concrete	Explore the use of coconut fibers in high-strength concrete to optimize the fiber's aspects	Increased compressive, flexural and tensile strengths Enhanced energy absorption in comparison to high-strength concrete	Best performance with 1.5% fiber content (by cement mass) at 50 mm length
Khan et al. (2020) [89]	Pakistan	Coconut fiber reinforced silica fume modified concrete	Optimizing thickness design of concrete road	Increased compressive, split tensile strengths, energy absorption and modulus of elasticity for coconut reinforced concrete versus plain concrete at 15% silica fume.	Recommended for concrete pavement use
Kenaf					
Elsaid et al. (2011) [90]	USA	kenaf fiber reinforced concrete	Characterize the mechanical properties of kenaf fiber reinforced concrete	Similar or lower strength than plain concrete Increased ductility and energy absorption	More water is required for suitable workability Suggested for impact-resistant applications
Mohsin et al. (2018) [91]	Malaysia	kenaf concrete slab	Study the behavior of kenaf fiber concrete slabs and improvement in shear capacity	Increased flexural strength, reduced crack propagation and improved ductility	No regain of shear capacity (lost due to decreased thickness) by adding fibers
Baarimah and Mohsin (2018) [92]	Malaysia	kenaf fiber concrete/hybrid (steel/kenaf)	Evaluate behavior of kenaf fiber or hybrid (kenaf-steel) fiber reinforced concrete	Increased mechanical properties with steel fibers Compressive strength improved with high % of steel with kenaf fibers (hybrid) Flexural strength was improved with even low steel hybrid mix Failure patterns changed from brittle to ductile	Hybrid combination of kenaf-steel can be applied for flexural applications
Muda et al. (2019) [93]	Malaysia	kenaf fiber mesh reinforced concrete	Investigate the impact resistance relationship with kenaf mesh reinforcement	Enhanced first crack and ultimate resistance with kenaf fiber mesh as compared to control specimen. Increased impact resistance with kenaf mesh having a higher diameter for the same thickness of slab	
Mahzabin et al. [94]	Malaysia	Kenaf fiber reinforced concrete	Compare kenaf fiber composite concrete with normal concrete in terms of mechanical properties	Equal or slightly low compressive strength, lower density, low slump and higher absorption than normal concrete Improved split tensile strength and flexural capacity	
Zhou et al. (2020) [95]	China	Kenaf reinforced high-strength concrete	Investigating the effect of natural fiber on high-strength concrete	Decreased compressive strength (12.2–46.2%) Increased flexural strength (30–67%)	The optimum fiber content was 1%

Table 2. *Cont.*

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
			Sisal/Banana/Ramie		
Hu et al. (2018) [96]	Guangzhou, China	Fiber reinforced epoxy polymer concrete	Study the flexural behavior using sisal or ramie fibers	0.36% fibers caused 25.3% and 10.4% increase in flexural strength using ramie and sisal fiber, respectively without compromise on compressive strength Higher fiber % resulted in decreased strength	Suggested for highway pavements and bridges as they are subjected to both compressive and bending loads
Prasannan et al. (2018) [97]	India	Fiber reinforced concrete	Study the effect of sisal and banana fibers on concrete properties	Minor improvements in compressive and split tensile strength Substantial increase in the flexural strength	Recommended for flexural applications where depth needs to be reduced
Frazao et al. (2018) [98]	Portugal	Sisal fiber cement composite reinforced lightweight concrete	Experimentally investigate the mechanical behavior of the composite reinforced concrete	Improved modulus of elasticity and tensile strength Reduced compressive strength, workability and more water absorption	Recommended for applications needing ductility
Okeoloa et al. (2018) [99]	Kenya	Sisal fiber reinforced concrete	Investigating the mechanical properties at different % of sisal	Increased split tensile strength and modulus of elasticity Decreased compressive strength, water absorption and workability	1% sisal as optimum out of 0.5–2.0%
Mouli et al. (2019) [100]	India	Metakaolin and banana reinforced concrete	Explore the effect of banana fibers on concrete properties	Increase in compressive strength and tensile strength in comparison to plain concrete, along with greater cracking resistance	Fiber content beyond optimum may cause a negative impact on mechanical properties
			Jute		
Zakaria et al. (2017) [101]	Bangladesh	Jute fiber reinforced concrete	Evaluate the strength improvement in concrete using jute fibers	Increased compressive, flexural and tensile strength with 0.1% & 0.25% volume content and 10 mm & 15 mm fiber length Jute yarn was found to be more suitable for concrete than jute fiber	Jute yarn was recommended for concrete due to renewability, low cost and strength improvement
Zia and Ali (2017) [102]	Pakistan	Fiber reinforced canal lining	Study behavior of jute fiber reinforced concrete in crack control of canal-lining	Jute fiber concrete showed 61% decreased slump, 31% compressive strength drop but 87% enhanced absorbed energy and better tensile strength than plain concrete lining	Suggested to use for controlling the cracking rate in canal lining
Akasaka et al. (2018) [103]	Japan	Fiber reinforced concrete (ring restrained specimen)	Experimentally observe the effect of incorporating jute for reducing high-strength concrete spalling	Negligible spalling with jute fibers.	Can be used in combination with ring restraint for control of spalling
Dayananda et al. (2018) [104]	India	Jute fiber reinforced concrete	Investigate the effect of raw jute on the compressive strength of concrete	Improved compressive strength as compared to control concrete Optimum fiber content was 0.4% after which strength and workability reduced	It's important to find the optimum dosage of fibers

Table 2. *Cont.*

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Kundu et al. (2018) [105]	India	Jute fiber concrete paver blocks	Study jute fibers for improvement of strength and flexibility of concrete paver blocks	Surface modified (using SBR latex and tannin) jute fibers increased compressive strength, flexural strength and flexural toughness by 30%, 49% and 166%, respectively.	It is recommended as a paver material as it enhances mechanical performance and can potentially reduce life cycle cost as It extends the service life
Islam and Ahmad (2018) [106]	Saudi Arabia	Jute fiber reinforced concrete	Evaluate the impact of different dosages of jute fibers on fresh and hardened properties of concrete. Also, studying the effect of fiber length and volume	Increase in fiber content caused decrease in slump Mixed influence on compressive strength depending on fiber content, type and size Flexural strength was reduced but the number of cracks/crack widths was lowered	Care to be exercised during mix design with fiber size and proportion
Zhang et al. (2019) [107]	China	Jute fiber reinforced high strength concrete	Explore effect of the water–cement ratio, jute fiber length, and jute fiber content on the high-strength concrete properties	Improved mechanical properties with optimum features (fiber content = 3 kg/m^3, fiber length = 16 mm and W/C = 0.3)	Need for exploring the acidity and alkalinity of natural fibers and cement
Ahmad and Ali (2020) [108]	Pakistan	Reinforced (Steel/GFRP) concrete walls with jute fibers	Augment the impact resistance of reinforced concrete walls	Jute reinforced concrete showed better toughness as compared to plain concrete. The GFRP and jute concrete combination was found to be the best.	Jute fibers recommended as sustainable material keeping in view the optimum fiber length, content and mix design
Zhang et al. (2020) [109]	Singapore	Fiber reinforced ultra-high performance concrete	Study high-temperature behavior of ultra-high performance concrete with jute fibers	More jute fiber is required to counter the thermal spalling compared to synthetic fibers. Weathering effects did not have any significant impact on the basic mechanical properties.	
Khaleel et al. (2021) [110]	India	Jute reinforced masonry bricks	Investigation of mechanical properties (fiber reinforced vs. textile reinforced)	Higher effectiveness of fiber reinforcement against textile reinforced. Enhanced energy absorption capacity	Can be utilized in earthquake zones
			Pineapple		
Irawan and Idris (2019) [111]	Indonesia	Fiber reinforced foamed concrete	Investigate behavior of foamed concrete with the addition of pineapple and polypropylene fiber	The compressive and flexural strengths both increased with the increase in fiber content with 0.4% polypropylene fiber (of total volume) with 12 mm length gave the maximum strengths. The fibers also reduced the microcracking of the concrete	The authors suggested using pineapple & polypropylene fibers for non-structural and structural concrete elements
Esper and Canseco (2020) [112]	Philippines	Pineapple fiber reinforced concrete	Study the effect of pineapple leaf fiber on concrete properties	Due to hydrophilic nature, treatment is required for addition of fibers into a cementitious material. The highest tensile strength (parallel to surface) and flexural strength were observed for 1% fiber content (w/w cement) out of 1.4 and 7% with 4% NaOH treatment	Pineapple fiber can be used as a low-cost and renewable source with special attention to optimum content and fiber treatment

It is evident from Table 2 that the use of natural fibers in concrete is one of the major applications of biocomposites as a construction material. Many researchers around the globe have explored the efficacy of natural fibers in concrete for augmenting mechanical properties. The merits of using natural fibers include low cost, corrosion resistance, low thermal conductivity, non-toxicity and renewability [14,113]. The fresh properties of concrete (slump and workability) are decreased by fibers similar to steel fibers. In terms of compressive strength, typically, the addition of natural fibers results in similar strength or slight reduction [65,67,71,74,77], which may be attributed to lower density and softness of natural fibers as compared to their synthetic counterparts like glass and steel. For example, Page et al. [65] observed compressive strengths of 38.28 MPa, 43.95 MPa and 40.72 MPa using 12 mm, 24 mm and 36 mm long fibers, respectively (0.3% fiber content). Whereas the control strength without fibers was 46.39 MPa. Nevertheless, the compressive strength in some instances is higher than the reference concrete, prominently in the case of treated jute fibers. For example, concrete paver blocks with modified jute fiber exhibited compressive strength of 31.3 MPa compared to 27.5 MPa for blocks with unmodified fibers and 26.2 MPa for unreinforced blocks [105]. Conversely, the natural fibers in concrete tend to improve the split tensile strength, flexural strength, impact resistance, shear strength, energy absorption, and deflection capabilities. In other words, their addition increases the concrete's toughness and ductility like steel fibers by providing crack resistance and more distributed cracking instead of large cracks. Moreover, natural fibers also help reduce the early age shrinkage in high-performance concrete as they provide an internal curing effect and enhanced volumetric stability [69,114]. A recent advancement in fiber reinforced concrete is structural health monitoring and damage diagnosis using non-destructive/wireless methods [115]. It has been used for synthetic fibers; however, it can be explored for natural fiber composites.

It is pertinent to mention that the improvement in mechanical properties is with reference to unreinforced concrete, whereas the mechanical properties may reflect lower values compared to synthetic fibers (comparable in certain cases). Another variant in this regard is a hybrid combination [92] of synthetic and natural fibers to reach a compromise between strength requirements and sustainability. Moreover, it is vital to take care of certain factors while using natural fibers in concrete like mix design [106], fiber content [100], fiber length [108], treatment (for countering hydrophilic nature) [112], acidity/alkalinity of natural fibers/cement [107]. For example, soaking hemp fiber in 0.24% NaOH solution for 48 h results in 80% and 54% increase in tensile strength and elastic modulus, respectively [116]. The surface treatment plays an important role in improved fiber-matrix interface, leading to a strong composite having higher interfacial shear strength [36]. Hence an optimized fiber content, treatment, and mix design are necessary to benefit from using natural fibers as reinforcement in concrete.

4.3. External Strengthening Agent

Natural resources are depleting rapidly, and the construction sector uses the abundance of the planet's natural resources [61]. In the case of damaged buildings or components, the demolishing and rebuilding processes put an immense burden on available materials. The strengthening agents in the form of plates, jackets, and wraps have been used in the past, recently replaced by Fiber Reinforced Polymers (FRP) made of glass, carbon, and aramid. Synthetic FRPs provide numerous advantages for strengthening structures/members such as corrosion resistance, large deformations handling capacity, and high strength-to-weight ratios [106]; however, they are costly and have high environmental impacts [117]. Table 3 exhibits natural fiber reinforced polymers (NFRP) as a structural strengthening agent.

Table 3. Natural fiber composites as an external strengthening agent.

Author (Year)	Region	Material Combination	Objective(s)	Findings	Weakness/Recommendation
			Flax		
Takasaki et al. (2014) [118]	Japan	Reinforced concrete beams strengthened by Flax fiber sheets	Study the shear strengthening effect of Flax fabric	22–72% improvement in shear strength of the beam Higher number of layers provided higher strengths	The direction of fiber in applied sheets influences the strengthening effect (WEFT direction better than WARP)
Yan et al. (2015) [119]	Germany	Concrete beams with coir (coconut) fibers and FFRP wrapping	Investigate the effectiveness of FFRP wrapping for concrete beams	Increased mechanical properties (flexural strength, deflection and ultimate load) More strengthening with more layers of wrapping Coir fibers augmented the lateral load capacity and fracture energy	FFRP can be used for strengthening of structures with an adequate intervention for ensured durability.
Huang et al. (2016) [120]	China	Concrete beams with external FFRP plates	Study flexural performance of FFRP strengthened concrete beams	Increased load-bearing capacity, deflection, ductility and energy absorption with FFRP strengthening Comparable load-bearing capacity to CFRP and GFRP	Lower tensile strength and modulus compared to CFRP and GFRP
Luccio et al. (2017) [121]	France	Reinforced concrete walls strengthened by flax FRP strips	Assess the feasibility of strengthening RC walls using flax FRP	Up to 150% strength enhancement and 30% increase in ductility were observed due to FFRP comparable to carbon FRP strips.	Authors recommended using FFRP for seismic retrofitting due to high displacement capacities with a suggestion for further experimental explorations.
Wang and Chow (2018) [122]	New Zealand	Concrete slabs with coconut fibers strengthened with flax fiber reinforced polymer (FFRP)	Evaluate the impact resistance of the FFRP wrapping and finding the more effective configuration	Better impact resistance, improved structural integrity under impact loading and more energy absorption capacity for slabs having fibers and FFRP wrap	Can be used for pavements or other structures having impact loads
Wang et al. (2019) [18]	Germany	Wooden beams externally strengthened using flax FRP	Compare Flax, Basalt and Glass FRP as external flexural strengthening agent	Flax FRP exhibited higher flexural load capacity than basalt and comparable with glass FRP The capacity increased for hybrid layer and a greater number of layers but the failure modes changed to debonding	Can be used for beam strengthening but cost provisions (in comparison to deep beam) and optimum number of layers must be used
Guadagnuolo and Faella (2020) [45]	Italy	Masonry beams strengthened with flax fiber fabric for seismic strengthening	Assess the retrofitting efficiency of masonry ring-beams with flax fabric for existing buildings	Enhanced seismic performance, increased resisting moments and deformation capacities compatible with adjoining masonry walls	Recommended for monumental buildings
Chen et al. (2020) [123]	China	Reinforced concrete beams strengthened by Natural FRP	Investigate the feasibility of natural FRP as replacement of synthetic FRP in structural strengthening upgrades	Significant (41%) increase in load-carrying capacity of RC beams (better than CFRP) and 20–40% cost efficiency Flax (particularly unidirectional) FRP achieved the best strengthening effect and cost-efficiency	Long term durability still unknown.Lower effective bond length of jute (more vulnerable to debonding)

Table 3. *Cont.*

Author (Year)	Region	Material Combination	Objective(s)	Findings	Weakness/Recommendation
			Hemp		
Siriluk et al. (2016) [124]	Thailand	Reinforced concrete beam with HFRP (shear strengthening)	Investigate the shear strengthening effect of HFRP	Increased shear capacity Better strength with uni-directional weaved wrap as compared to matte weaving	HFRP costs are significantly lower than CFRP and GFRP
Ghalieh et al. (2017) [125]	Lebanon	Concrete columns with hemp fiber reinforced polymer (HFRP) confinement	Study HFRP efficacy for column strengthening along with factors like number of layers and column slenderness ratio	Increased compressive strength, ductility and energy absorption capacities.More capacity enhancement with a greater number of wraps	Ultimate stress impacted by the column's slenderness ratio
Bitar et al. (2020) [126]	Lebanon	Unreinforced masonry walls externally strengthened by hemp fiber fabric	Investigate the effect of hemp fabric in enhancing flexural capacity	Substantial increase in flexural capacity using hemp fabric (up to 500%) along with enhanced deflectionshemp fiber rupture governed the majority of failure modes	Going beyond the optimum reinforcement ratio (2% in this case) may result in a loss of ductility
			Kenaf/Jute/Sisal		
Sen and Reddy (2013) [127]	India	Reinforced concrete beams strengthened with jute composites	Study jute fibers for structural retrofitting of beams	Approx. 60% increase in the load-carrying capacity of beams (full wrap) 25% strength enhancement with strip wrappingHigh deformability index as compared to CFRP and GFRP	Jute FRP recommended for structural strengthening
Hafizah et al. (2014) [128]	Malaysia	Reinforced concrete beam with kenaf composites	Study of kenaf fiber application for strengthening of beams (flexural strength, deflections etc.)	More fiber content resulted in higher strength of kenaf composites Enhanced flexural strength (40%), deflection (24%) and stiffness	Need to investigate long-term durability
Sen and Reddy (2014) [129]	India	Reinforced concrete beams strengthened with sisal composites	Investigate the structural strengthening characteristics of sisal composites	Heat treatment increased the flexural and tensile strength of sisal FRP About 110% and 65% strengthening was achieved using full and strip sisal wrapping, respectively	Sisal composites also provide an edge in terms of life cycle environmental impacts
Sen and Paul (2015) [130]	India	Concrete cylinders confined with natural FRP	Evaluate the confinement strength/modulus parameters of fully and strip-wrapped concrete cylinders by natural jute and sisal fabrics	Approx. 65% and 50% strength increment using sisal and jute FRPs, respectively	Lower strengthening in comparison to GFRP and CFRP but more sustainable
Tan et al. (2017) [131]	China	Jute FRP confined sisal fiber concrete cylinders	Experimentally study the compressive behavior of jute polymer confined sisal fiber concrete	Jute FRP enhanced the compressive strength of plain and sisal fiber concrete with more increase with sisal fibers 18%, 35% and 58% increase with 1, 3 and 5 layers, respectively Sisal fiber increased the fiber efficiency but not the ultimate strain. More layers increased the ductility	Suggested further studies on axial/flexural strengthening of concrete and masonry. Durability needs to be examined

Table 3. *Cont.*

Author (Year)	Region	Material Combination	Objective(s)	Findings	Weakness/Recommendation
Alam and Riyami (2018) [132]	Malaysia	Reinforced concrete beams with natural composite plates (shear strengthening)	Produce high-strength composite plates with treated/untreated kenaf, jute and jute rope for shear strengthening of beams	The maximum natural fiber content for fabrication was 45% 35%, 36% & 34% higher shear strengths for beams strengthened with untreated kenaf, jute and jute rope plates, respectively 10%, 23% & 31% higher shear strengths for beams strengthened with treated fiber plates	Important to investigate the optimum fiber content with each composite for better structural performance
Omar et al. (2022) [133]	Malaysia	Plain concrete beam strengthened by kenaf FRP plates	Optimization of varying kenaf FRP plates for flexural strengthening of beams	Increased flexural strength and deformability by all 4 variants of kenaf FRP Main failure mode in plate rupture utilizing the full strength	Thicker kenaf FRP plates provide the best performance.
Maulana et al. (2022) [134]	Malaysia	Foam concrete beam strengthened by kenaf FRP sheet	Experimental investigation of strengthened beam behavior and strength prediction	Increased lengths of the sheet provided higher flexural capacities More layers of KFRP reduced the ultimate displacement Finite element modelling resulted in models with average 10% discrepancies with experiments	The major failure mode was shear failure, and only the specimen with the longest FRP sheet failed in rupture
Bamboo					
Chin et al. (2019) [135]	Malaysia	Reinforced concrete beams strengthened with bamboo fiber composite plate	Test the effectiveness of the plates as external strengthening material in flexure	10–12% increase in flexural strength as compared to un-strengthened beam and diversion of cracks from vertical to diagonal at the end of plates	Recommended for flexural strengthening of RC beams

Modern FRPs have incorporated natural fibers as they are cheap and maneuverable. The natural FRPs used for retrofitting/strengthening include sheets/wraps, plates, and strips applied according to the requirement (axial strengthening, flexural strengthening, or shear strengthening). Unlike fiber reinforcement, natural fiber strengthening and its impacts vary more in fiber type, structural member, parent material, and applied configuration. The common observation is the improvement in mechanical properties of structural members having NFRP strengthening compared to un-strengthened members. Although the strength enhancement is lower compared to Carbon and Glass FRPs, the strength increase is comparable in certain cases. Moreover, the energy absorption capacity and ductility of NFRP strengthened elements exceed the synthetic FRPs. For example, Wang et al. [18] observed that one wrap of Flax FRP enhanced the maximum load carrying capacity of the control specimen from 2.8 kN to 4.5 kN, whereas the strength with one wrap of Glass FRP was 4.8 kN (very close to flax FRP). The areas of concern in their application are their long-term durability [123], fiber content [126], and the direction of fibers in FRP [118].

Moreover, the natural fibers tend to be combustible as cellulose and hemicellulose start decomposing near 200 °C [136]. The thermal performance is governed by factors like fiber type, surface treatment, matrix type, fillers, and fiber content [37]. Hence, there are methods to analyze the thermal performance of natural fiber composites. These methods include dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA) [37]. Moreover, macroscale flame retardants (like mineral hydroxide, hydroxy carbonates, borates-based, phosphorus-based and halogenated flame retardants) and Nanoscale retardants (including layered silicates and carbon family nanomaterials) can be used to reduce combustibility [136]. Macroscale retardants have the drawback that they need higher dosages and lessen the mechanical properties of composites, whereas nanoscale retardants can cause agglomeration. A balance needs to be established to optimize the desired properties of composites.

4.4. Internally Filled FRP Tubes

Another important structural application of composites is FRP tubes filled with masonry or concrete. The FRP forms the internally hollow confinement with a rough internal surface for bonding, whereas the designed concrete mix is filled inside it in the fresh state and allowed to harden and attain strength. Synthetic fibers have been used quite frequently for such structural beams and columns. Recently, flax fibers FRP have also been used by researchers in combination with other natural fibers (for strengthening the concrete). Table 4 shows a few studies and their findings regarding this hybrid structural application. Currently, flax has been used predominantly as the material providing the confinement to recycled concrete/brick masonry aggregates with encouraging results in terms of strength enhancement and use as compressive/flexural members. However, other fibers need more experimental exploration for similar applications.

Table 4. Internally filled natural fiber composite tubes.

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Yan and Chouw (2013) [19]	New Zealand	Flax FRP tube filled with coir reinforced concrete	Investigate the efficacy of coir as concrete reinforcement and flax FRP as confinement material	Improved axial compressive strength and ductility with FFRP confinement for both plain and coir reinforced concrete. (also, with increased tube thickness) Significant enhancement in ultimate lateral load and mid-span deflection using FFRP tube.	FFRP-CFRC composite columns have the potential to be used as axial/flexural structural members
Yan et al. (2017) [137]	China	Flax FRP tube filled with masonry recycled aggregate concrete (partial replacement)	Investigate the compressive behavior of the hybrid material	FFRP tube enhanced the strength of recycled aggregate concrete with more strength enhancement for higher concrete strength	
Huang et al. (2017) [138]	China	Flax FRP tube filled with recycled aggregate concrete containing clay brick aggregate	Investigate the compressive behavior of the hybrid material	FFRP tube confinement significantly increased both strength and ductility of the confined cylinders	
Gao et al. (2022) [139]	China	Sisal fibers in recycled aggregate concrete confined by jute FRP tube	Study the compressive behavior of sisal fiber recycled aggregate concrete in jute FRP tube	Increased compressive strength and ultimate strain provided by jute FRP Bridging effect and slow lateral dilation provided by sisal fibers	Fiber orientation in recycled aggregate concrete plays an important role in ultimate compressive strength and strain

4.5. Bio-Based Sandwich Panels

Biocomposites have also shown promise as replacement of synthetic fibers for making composite panels. The use of natural fibers in bio-based panels is highly encouraging, specifically from the Canadian perspective. Table 5 shows the findings of the studies with foamed core combined with natural fiber skins to make sandwich panels. Prominently, the bio-based panels have used flax as a substitute outer skin material; nonetheless, they do not provide the same performance as glass skins and need thicker layers to provide similar strength.

Table 5. Bio-based sandwich panels.

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Hu et al. (2007) [117]	USA	Bio-based skin for sandwich panels	Structural design and performance evaluation of the sandwich roof	Wrapping the bio-based skins provided better performance than the stacked layers. The model satisfied the deflection criteria.	Recommended investigating the creep, thermal analysis and inflammability further
CoDyre and Fam (2017) [20]	Canada	Foam-core panels with flax composite skins	Investigate axial compressive behavior of the sandwich panels with flax composite skins	Flax FRP sandwich specimens exhibited about one-third of the strength given by sandwich specimens with glass FRP skin Longer panels failed due to global buckling at peak load; whereas' shorter panels had localized failures	Design can be optimized according to the usage requirements
Betts et al. (2017) [140]	Canada	Sandwich Panels having foam cores and Flax FRP facings	Investigate failure mechanisms of sandwich foamed panels with FFRP facings	Flax FRP facings were found suitable for sandwich panels (having polyisocyanurate foams)	The failure mechanisms depend on the facing thickness
CoDyre et al. (2018) [141]	Canada	Foam-core panels with flax composite skins	Investigate axial & flexural behavior of the sandwich panels with flax composite skins	Three-layered flax reinforced skin (only 17% thicker than one glass FRP provided equivalent flexural and axial strengths at all three core densities with slight deviations The enhancement in axial & flexural strength was more for specimens with FFRP skins as compared to specimens with GFRP	FFRP skins can be used to replace GFRP with a higher number of layers. Cost analysis needs to be done

4.6. Insulation and other Applications

Hempcrete has been used widely for insulation purposes. The use of natural fiber composites, including hemp-lime concrete as insulating materials, are presented in Table 6. Moreover, the other applications of biocomposites include:

- Pipes made of plain-woven (bidirectional) flax fabric [142]
- Flax-based wind turbine blade [143]
- Sound absorbing materials [144]
- Kenaf-based wall cladding [145]
- Biocomposite boards as wood replacement [146,147]

Table 6. Biocomposites as insulating materials.

Author (Year)	Region	Material Combination	Objectives	Findings	Weakness/Recommendation
Ibraheem et al. (2011) [23]	Malaysia	Insulation boards (kenaf)	Development of green insulation boards using polyurethane with kenaf fibers	50% kenaf fiber content was optimum (out of 40%, 50% & 60%) Thermal conductivity reduced with an increase in fiber content The NaOH treatment of kenaf fibers increased the mechanical properties.	The use of optimum content and proper treatment of fibers keeping in account the porosity and bonding of fibers can help produce high-quality insulation products.
Korjenic et al. (2016) [46]	Austria	Plant-based building facades (flax, hemp & jute)	Present results regarding insulation material based on natural fibers	Optimal mix of materials out of all combinations provided thermal performance comparable to market materials	Recommended due to their thermal performance and smaller PEI (primary energy input) compared to glass fibers.
Brzyski et al. (2017) [148]	Poland	Hemp Flax composite material	Study various combinations of flax-hemp composites foe low energy buildings	Composites showed low strength, low density, low thermal conductivity and high absorptivity.	Recommended as insulation/filler or for external wall construction
Costantine et al. (2018) [149]	France	Hemp lime concrete for insulation	Assess the performance of the building in terms of thermal insulation	Reasonable thermal comfort (some high relative humidity areas)	Limitations in terms of site implementation of hemp concrete as compared to other materials
Garikapati et al. (2020) [68]	Canada	Flax lime concrete/beams with jute fabric mesh	Study flax shives mixed with a lime-based binder work as a construction material	Jute fabric was effective in crack control	Recommended for infilling masonry blocks and for filling wall cavities as insulation

4.7. Key Concerns and Challenges

The current applications of biocomposites as construction materials discussed above have the following concerns and challenges.

Limited real-life applications: The real-life applications of biocomposites are promising but limited and require industrial expansion to instill confidence in their benefits and applicability in construction.

Varying fiber properties: Natural fibers in cementitious composites/concrete improve their post-cracking behavior i.e., toughness. The major concern is the variability of natural fibers as each fiber has its composition and properties. Hence, it is important to get the optimum fiber content, length, and type (treated/untreated) for a particular member [100,106,108,112]. Moreover, natural fibers tend to decrease workability and increase air content and water demand which can be inconvenient in massive concrete works.

Specific design and unknown long-term durability: Natural fiber reinforced polymers (FRP) with adhesives have shown strength enhancement comparable to glass in a few cases. Like cementitious composites, these composites also need an optimized design [150] for each application with caution related to fiber content, member configuration, and direction of application of composites [118,123,126]. Higher fiber content generally enhances their strength but compromises ductility. Furthermore, their long-term ductility against open environments and weathering needs further investigation. Selecting the right fiber, content, and orientation in the composite and interventions for extending the service life of natural FRPs can serve the construction industries of countries rich in agricultural feedstock.

Explorations with other natural fibers: The current studies on filled FRP tubes and bio-based sandwich panels predominantly involve flax fibers. The other lignocellulosic fibers should be experimentally evaluated for similar applications to have a basis for sound comparison among fibers. Further, their long-term durability needs to be addressed as well.

Insulation design: Biocomposites have numerous non-structural applications like coverings, facades, and partitions but the applications that stand out are as insulation material and wood replacement [20,140,141,148,149]. The optimized mix design is necessary to get the best performance out of these materials. These can benefit the construction industry of countries like Canada, where wooden construction is common.

Site Implementation: Their site implementation is also a challenge. Technical innovation in a massive industry (construction) requires practical guidance for all stakeholders to understand the processes involved. Pieces of training and guidance programs in this regard can be fruitful.

5. Life Cycle Sustainability of Biocomposites

Biocomposites are perceived as environment-friendly and economical materials compared to synthetic composites due to their renewable ingredients. Table 7 provides the costs and environmental footprints of the natural fibers discussed in this article. It is evident that natural fibers have less environmental impacts than synthetic fibers like glass and carbon. However, more exploration is required, as depicted by the gaps in the table, specifically for environmental properties. Carbon fibers provide excellent mechanical properties among composites; nevertheless, they are costly and have environmentally low performance. However, a composite's renewable origin does not automatically make it a sustainable material [151]. It is important to evaluate all the life cycle stages of material, from raw material extraction to final disposal or recycling. Life cycle sustainability methods like life cycle assessment (LCA) [152] and life cycle costing (LCC) [153] are commonly used for holistic sustainability assessment, which considers all stages of a product's life cycle for case-to-case evaluation.

Table 7. Environmental and economic features of natural fibers along with chemical and mechanical properties [13,28,154–160].

	Major Chemical Components			**Physical/Mechanical Properties**								**Economy**	**Env. Properties**		
Fiber	**Cellulose (%)**	**Hemi-cellulose (%)**	**Lignin (%)**	**Density (g/cm^3)**	**Diameter (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPA)**	**Elongation at Break (%)**	**Moisture Content (%)**	**Thermal conductivity (W/Mk)**	**Price (US$/ton)**	**Embodied Energy (GJ/ton)**	**GHG emission (CO_2-eq/tonne fibre)**	**Water Footprint (m^3/kg)**
Flax	71–78	18.6–20.6	2.2	1.38	5–38	10–65	343–1035	50–70	1.2–3	7	0.055	2.1–4.2	59–86	349	-
Hemp	70.2–74.4	17.9–22.4	3.7–5.7	1.47	10–51	5–55	580–1110	30–60	1.6–4.5	8	0.25	1.0–2.1	-	406	-
Jute	61–71.5	13.6–20.4	12–13	1.23	5–25	0.8–6	187–773	20–55	1.5–3.1	12	-	0.4–1.5	-	548	1.55
Kenaf	45–57	21.5	8–13	1.2	12–36	1.4–11	295–930	22–60	2.7–6.9	6.2–12	-	0.3–0.500	-	418	0.7
Abaca	56–63	21.7	12–13	1.5	10–30	4.6–5.2	430–813	31.1–33.6	2.9	14	-	0.345	-	-	-
Bamboo	26–65	30	5–31	0.85	25–88	1.5–4	270–862	17–89	1.3–8	11–17	-	0.5	-	-	-
Banana	63–64	10	5	1.35	12–30	0.4–0.9	529–914	27–32	5–6	10–11	-	0.89	-	-	-
Coir	36–43	0.15–0.25	41–45	1.2	7–30	0.3–3	175	6	15–25	10	0.047	0.2–0.5	-	-	-
Cotton	85–90	5.7	0.7–1.6	1.21	12–35	15–56	287–597	6–10	2–10	33–34	0.03	1.5–4.2	-	-	2.07
Pineapple	81		12.7	1.5	8–41	3–8	170–1627	60–82	1–3	14	-	360–550	-	-	-
Ramie	68.6–76.2	13–16	0.6–0.7	1.44	18–80	40–250	400–938	61.4–128	2–4	12–17	-	2000	-	-	-
Sisal	65	12	9.9	1.2	7–47	0.8–8	507–855	9–22	1.9–3	11	0.04187	600–700	7.2–7.96	-	-
Softwood	40–44	25–29	25–31	0.30–0.59	30	1	45.5	3.6–14.3	4.4	-	-	4.4–5.5	-	-	3.03 *
Hardwood	43–47	25–35	16–24	0.3–0.88	16	3.3	51–120.7	5.2–15.6	-	-	-	4.4–5.5	-	-	-
Carbon	-	-	-	-	-	-	-	-	-	-	-	12.5	130	29,500	-
Glass	-	-	-	2.5	15–25	-	2000–3500	70–73	2.5	-	-	1.2–1.8	30	2700	0.041
Natural (general)												0.2–1.0	4	400	-

* *from SimaPro.*

5.1. Environmental Performance

Studies involving biocomposites' life cycle assessments (LCA) have been scarce, specifically in their use as a construction material [21]. It can be observed that a search with the keywords "LCA of biocomposites" on Compendex Engineering Village returns less than 65 records (as of July 2022). Important life cycle studies on natural fiber composites having direct and indirect use in the construction sector are discussed. Natural FRP made of flax fiber have lower environmental impacts than jute and carbon FRP; however, the extensive use of epoxy adhesive reduces environmental and cost benefits [64]. Batouli and Zhu [161] performed a comparative LCA between kenaf and glass fiber-based insulation panels. The cradle-to-gate LCA using the Ecoinvent database revealed kenaf-based insulation panels to be environmentally positive in all impact categories. Escamilla et al. [162] conducted LCA for vegetable fibers in concrete and reported significant environmental savings. Moreover, it was also suggested to incorporate sensitivity analysis and be careful in selecting functional unit and disposal scenarios.

Similarly, Arrigoni et al. [163] conducted a life cycle analysis of hempcrete blocks, excluding the end-of-life stage (due to non-reliable data). Raw material production for hempcrete was the main contributor to environmental impacts. Moreover, the binder mixture amount and composition also significantly impacted the transport distance. Carbon intake during hemp growth and carbonation during the use phase made the hempcrete blocks carbon negative, called as "effective carbon sinks". However, the binder production stage was highly impactful, which may incite the use of different or less binders with caution regarding the changes in blocks' chemical and mechanical properties. Similarly, raw material transport distances were vital in terms of environmental impacts. A recent study by Diaz et al. [164] has also highlighted the carbon storing capacity of hemp concrete and its low environmental impacts compared to other building materials.

An interesting study that combined LCA and mechanical properties of composites [165], comparing flax fiber versus glass in polypropylene revealed that a similar substitution provided 6% lighter composites with 10–20% lower environmental burdens. Furthermore, the merits included low fuel consumption due to lightweight, low emissions during use, and a manageable end-of-life phase. However, the drawback in terms of "Eutrophication" was also highlighted. Coupled micromechanical modeling involves the initial design of the composite and subsequent LCA of the model. This enables the decision-makers and designers to know which product is optimum for mechanical performance and sustainability.

As discussed above, the most prominent application of biocomposites in construction is using fibers in cementitious composites. Merta et al. [166] compared the natural fibers, including flax, hemp, and sea grass, against synthetic Polyacrilonitrile (PAN) fibers as reinforcement in concrete. The system boundary was defined as 'cradle to gate' because of unknown durability of fibers in the cementitious mix. The LCA indicated that the natural fibers had lower environmental impacts than synthetic ones except for flax in eutrophication and aquatic ecotoxicity categories. These high impacts were related to using a high amount of water, fertilizers, and emissions due to crop cultivation. Therefore, using fibers in concrete can benefit cost and environmental implications if used as a substitute for steel or glass. Compared to plain concrete, biocomposites can enhance mechanical properties, but the cost and impacts will also be higher because of additional ingredients. However, in the broader picture, the environmental benefits of natural fibers outweigh the demerits. Recent LCA studies for biocomposites (not confined to construction) with their prominent features have been summarized in Table 8.

Table 8. LCA studies on biocomposites.

Ref	Region (Year)	Main Concern Area/Emphasis	Biocomposite Type & Purpose	Functional Unit (FU)/System Boundary (SB)	LCA Method/Software/Inventory	Findings
[167]	Iran (2008)	Comparison of hybrid bio based composite with fully petroleum-based composite	Kenaf biocomposite as construction materials (with polyhydroxybutyrate)	FU: m^2 of usable floor/wall area SB: Cradle to gate (excluding transportation)	• ReCiPe • SimaPro • Ecoivent 3.2 • industry data • USLCI	Adverse effects of petroleum composites such as human toxicity, eutrophication, ecotoxicity and Indoor chemical emissions of polymers.
[168]	New Zealand (2008)	LCA of wood-fiber-reinforced polypropylene composite with 3 levels of contents (10, 30 and 50% by mass)	Wood fiber composites as construction and automotive material	FU: Material Service density	• SimaPro • Eco-Indicator 99	The use and disposal phase of wood composites are environmentally advantageous. Disposal (e.g., Incineration) claims some energy back
[169]	USA (2008)	LCA in comparison with glass and 2 waste treatment methods (landfill and composting)	kenaf fiber composites for automotive	FU: 1 kg of fiber reinforced composite (automotive part) SB: cradle to grave	• TRACI • Uncertainty Analysis	kenaf reduces non-renewable energy consumption by 23–24% and greenhouse gas emissions by 6–16% over glass but has more local environmental impacts (photochemical smog formation, acidification and eutrophication)
[156]	Poland (2016)	Comparative environmental assessment of plastic pallets from composites and biocomposites	1. Polypropylene (PP) 2. Glass 3. Jute 4. Cotton 5. Kenaf	FU: 1 heavy-duty plastic pallet (made by an injection molding process) SB: Cradle to gate	• SimaPro 8 • Ecoinvent 3.1 • ReCiPe method (Midpoint)	Jute and kenaf composites have lower environmental impact than PP composites with glass fiber or cotton. The negative impacts include use of toxic pesticides and impact factors like acidification, eutrophication, agricultural land occupation, particulate formation and human toxicity.
[150]	Denmark (2016)	Fiber selection for eco design	FFRP and GFRP	FU: Equivalent mechanical stiffness performance of 1 kg of GFC in different mechanical applications SB: Cradle to grave	• Ecoinvent 2.2 • Ashby method • GaBi 6 • ReCiPe method (Midpoint)	Low impacts for FFRP vs. GFRP. Optimized fiber and matrix content give max environmental advantage. Natural fibers use renewable sources, low energy consumption for production and less issues with disposal

Table 8. *Cont.*

Ref	Region (Year)	Main Concern Area/Emphasis	Biocomposite Type & Purpose	Functional Unit (FU)/System Boundary (SB)	LCA Method/Software/Inventory	Findings
[163]	Italy (2017)	Life cycle environmental impacts of a wall made of hempcrete blocks	Hemp (can be used as filling material/roof & floor insulation/Indoor & outdoor plasters and prefabricated panels	FU: 1 m^2 hempcrete block wall SB: Selective processes	• Producer & Literature • CED • Sensitivity Analysis	Hempcrete blocks act as carbon sinks due to their CO_2 uptake. The production phase is crucial (with factors like transport distance and binder composition as impacting factors)
[170]	Canada (2017)	Comparison of conventional beauty cover with hybrid bio-based cover		FU: A beauty cover of truck for 25 years/290,000 km SB: cradle to grave	• TRACI 2.1 • OpenLCA • SimaPro • NREL	Hybrid bio-based worked better than the current cover except for wood and water consumption
[171]	USA (2018)	Comparison of polylactic acid (PLA) composites	PLA composites with organic (flax/hemp/wood) and inorganic (glass/talc) fillers	SB: raw material acquisition, transportation, manufacturing, consumption, and end-of-life treatment.	• TRACI	Utilization of organic fillers produces a lower economic/environmental impact compared to inorganic fillers in PLA composites. (wood fillers along with recycling end of life were least damaging)
[172]	Columbia (2018)	LCA and LCC of four alternatives of banana fiber biocomposite using unsaturated polyester resin as matrix.	Columbian banana fiber biocomposites (for automotive, packaging and aerospace)	FU: Tensile test sample (460 mm × 400 mm × 5 mm) SB: Cradle to manufacture	• SimaPro 8.3 • ReCiPe Method (Endpoint) • Multi-criteria analysis (Shannon entropy method)	Biocomposite has lower cost and environmental impact than polyester, but its lower tensile strength and higher water absorption cause a lower overall performance comparing with the polyester The use of BF in biocomposites materials can avoid its disposal in landfills.
[173]	France (2019)	Environmental impacts of the End of life (EoL) treatments of wood flour (WF) reinforced polypropylene (PP/WF) and flax fibers reinforced polylactic acid (PLA/Fl)	1. Wood flour reinforced Polypropylene (PP/WF) 2. Flax fiber reinforced poly lactic acid (PLA/FI) (for automotive and buildings)	FU: Managing 1 Ton biocomposites waste SB: End of life	• Hybrid ReCiPe method (midpoint) • GABI software • Ecoivent 2.2 • Normalization • Sensitivity Analysis	Recycling EoL scenario presents the lowest environmental impacts, followed by industrial composting for PLA/Fl composite, and incineration for PP/WP. Recycling leads to the production of a secondary raw material avoiding environmental impacts
[41]	Belgium (2019)	LCA of fibers and recycling	Plant fibers mainly flax (used in automotive industry) ∗ Compression molded mat & injection molded short flax fibers	SB: Cradle to grave (incineration end of life)	• ReCiPe method • Simapro 7.2.3 • Ecoinvent 2.2 • ROM & Ashby method	Mat flax has low env imp than glass (reduced fuel consumption) Incineration end of life causes energy recovery More LCA studies needed for flax fiber

It can be observed from Table 8 that current LCA studies on biocomposites vary in terms of material combinations, functional units, system boundaries, and assessment methods. The selection of an appropriate functional unit is critical in comparative LCA studies for meaningful comparison. Similarly, the selection of system boundaries depends on the intended goal of the study and the availability/quality of data. Biocomposites have shown better environmental performance than synthetic composites; however, they have higher impacts in categories like acidification, eutrophication, agricultural land use, and human toxicity [156,169]. Additional LCA studies on biocomposites as a construction material can augment the current literature and help better understand their sustainability. Moreover, the techniques like sensitivity analysis and uncertainty analysis can be incorporated for identifying the highly impacting life cycle stages [163,173].

5.2. Economic Performance

The economic aspects of biocomposites have been investigated lesser than the environmental aspects. It is obvious from Table 7 that processed natural fibers have significantly lower costs than synthetic fibers, which gives a perception that the composites manufactured using these fibers will be economical. The economic benefits have been explored by some researchers [21,35,44,48,171,172]. The findings show that the ingredients for biocomposites and bio-based materials are abundantly available at a significantly low price compared to their conventional counterparts, like glass, steel, and carbon. Further, improved fuel efficiency and transportation are sources of cost-effectiveness. Moreover, the savings can also spring from the low energy requirements during their processing. For example, Akil et al. [174] identified the cheaper cost of kenaf fiber composites, whereas, Wambua et al. [175] pointed out less wear on the tools caused by natural fibers as compared to glass during manufacture. This leads to longer equipment service life and long-term savings in repair and maintenance.

5.3. Environmental and Economic Benefits

This section discusses the generic benefits of biocomposites (not confined to construction applications). The following characteristics of biocomposites can be projected towards their construction use.

- Biodegradability and the incorporation of renewable resources make them environment-friendly and facilitate end-of-life treatments/disposals [26,27,40]. Their incineration produces fewer impacts as compared to conventional plastics.
- Natural fibers have a low carbon footprint, greenhouse gas emissions and resource depletion compared to petroleum-based materials [13,28].
- Their production processes are less energy-intensive, and their lighter nature (in weight) helps their transportation. The low weight also helps automobile manufacture due to fuel efficiency [44]. The transport distance of raw materials is a critical factor. For example, the fibers imported from other countries can cost even more and produce more emissions than the locally available synthetic fibers.
- Compared to glass or carbon, natural fibers like hemp, sisal and flax have less health implications for industry workers. They also reduce the burden on the manufacturing equipment due to decreased abrasion.

5.4. Research Gaps and Future Needs

The identified research gaps and suggestions for future research related to biocomposites' sustainability are listed in this sub-section.

- Natural fiber-based biocomposites have a wide range of encouraging construction applications and bright sustainability prospects. Biocomposites' projected environmental benefits are based on limited studies. Therefore, detailed lifecycle-based assessments of biocomposites as building materials should be conducted to establish them in the world's construction market.

- Biocomposites' economic and social lifecycle impacts have been investigated less than their environmental aspects, as indicated by the low number of records on research databases. More studies on life cycle costing (LCC) and social life cycle assessment (sLCA) can enhance the current body of knowledge on biocomposites' sustainability.
- Introducing an innovative material in a well-established construction industry is daunting. Both mechanical properties and the life cycle sustainability aspects must be incorporated in decision and policy-making. This process necessitates a decision support framework that can incorporate complex criteria and rank the biocomposites against synthetic composites under various scenarios.

6. Conclusions

The construction sector is searching for innovative sustainable materials to reduce environmental impacts associated with conventional construction materials. Biocomposites possess natural constituent(s) and have recently received great attention because of their renewability and cost-effectiveness. This study reviewed the various applications of natural fiber-based biocomposites in the building sector as a potential substitute for conventional construction materials. The highlights are as follows:

- The research and development in biocomposites have received an exponential boost in the last five years due to their sustainability potential, specifically in the construction sector. Biocomposites primarily use natural fibers from plant sources (lignocellulosic fibers) like flax, hemp, jute, and kenaf. Their field applications include biocomposite bridges in the Netherlands and widely used hempcrete, which have paved the way for more bio-based structures.
- The most common application is using natural fiber as reinforcement in concrete. The current literature indicates that the compressive strength of natural fiber reinforced cementitious composites/concrete tends to be lower or comparable with concrete having no fibers. The decline in strength occurs due to fibers' low density and softer nature. However, the natural fibers addition results in enhanced post-cracking behavior, flexural strength, and impact resistance. Moreover, natural fibers also provide internal curing and reduce the early shrinkage for high-performance concretes. The challenges in its use are a selection of optimum fiber content, mix design, suitable fiber length, and the surface treatment method.
- The strength enhancement using natural FRPs for structural strengthening often lies below the synthetic composites; nevertheless, the strengthening effect is substantially higher than the un-strengthened specimens. Moreover, the natural FRPs also show higher ductility and energy absorption than carbon and glass FRP. The strengthening effect also depends on the number of FRP layers, fabrication, and direction of fibers. The concern related to natural FRPs is their long-term durability which must be addressed for longer service life.
- Natural fiber biocomposites have shown significant results as non-load-bearing members like insulation, boards, sound absorbers, facades and foamed sandwich panels (which can also be load-bearing). Biocomposite insulations provide thermal performance and comfort comparable to market materials. The applications like bio-based panels and natural FRP tubular members need more exploration in terms of fibers, as current studies mainly cover flax fibers.
- Biocomposites promise to be economical and environmentally friendly construction materials because of their natural origin; however, evaluating their life cycle assessment and cost is vital to have a broader picture of their prospects. The available studies along with the economic and energy footprint data validate their benefits to some extent. However, the current literature is deficient in life cycle studies of biocomposites, particularly as a construction material. Moreover, there are environmental impact categories where biocomposites underperform compared to synthetic composites. Therefore, it is necessary to have more lifecycle-based case studies for various scenarios. A life-cycle decision support tool can present a comprehensive

package to planners, designers, and other construction stakeholders to select and rank biocomposites for different applications and regions.

Author Contributions: H.A.: Conceptualization, Methodology, Formal analysis, Writing—original draft, G.C.-S.: Writing—review & editing, Project administration. K.H.: Supervision, Writing—review & editing. R.S.: Supervision, Writing—review & editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by funding support from Natural Sciences and Engineering Research Council of Canada (NSERC), Biocomposite Research Network (BCRN) and University of British Columbia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Department of Economic and Social Affairs of United Nations. *World Population Prospects 2019*; United Nations, Ed.; United Nations: New York, NY, USA, 2019; ISBN 9789211483161.
2. Statista. Global Construction Industry Spending 2014–2019, with Forecasts up Until 2035 Published by Raynor de Best, 15 February 2021. The Construction Industry Grew to a Spending Value of Close to 12 Trillion, U.S. Dollars before the Coronavirus Pandemic, and Is Expecte. Available online: https://www.statista.com/statistics/788128/construction-spending-worldwide/ (accessed on 16 April 2021).
3. Ferrer, A.L.C.; Thomé, A.M.T.; Scavarda, A.J. Sustainable urban infrastructure: A review. *Resour. Conserv. Recycl.* **2018**, *128*, 360–372. [CrossRef]
4. Thomé, A.M.T.; Ceryno, P.S.; Scavarda, A.; Remmen, A. Sustainable infrastructure: A review and a research agenda. *J. Environ. Manag.* **2016**, *184*, 143–156. [CrossRef] [PubMed]
5. Yadav, A.; Yadav, N.K. A Review on Comparison of Ancient and Modern Construction Materials in Civil Engineering. *Int. J. Res. Appl. Sci. Eng. Technol.* **2016**, *4*, 254–256.
6. Flower, D.J.M.; Sanjayan, J.G. Green house gas emissions due to concrete manufacture. *Int. J. Life Cycle Assess.* **2007**, *12*, 282. [CrossRef]
7. Yeheyis, M.; Hewage, K.; Alam, M.S.; Eskicioglu, C.; Sadiq, R. An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technol. Environ. Policy* **2013**, *15*, 81–91. [CrossRef]
8. Chang, Y.; Ries, R.J.; Wang, Y. The quantification of the embodied impacts of construction projects on energy, environment, and society based on I-O LCA. *Energy Policy* **2011**, *39*, 6321–6330. [CrossRef]
9. Asadollahfardi, G.; Asadi, M.; Karimi, S. Life-Cycle Assessment of Construction in a Developing Country. *Environ. Qual. Manag.* **2015**, *24*, 11–21. [CrossRef]
10. Khan, R.; Jabbar, A.; Ahmad, I.; Khan, W.; Khan, A.N.; Mirza, J. Reduction in environmental problems using rice-husk ash in concrete. *Constr. Build. Mater.* **2012**, *39*, 6321–6330. [CrossRef]
11. Dahlbo, H.; Bachér, J.; Lähtinen, K.; Jouttijärvi, T.; Suoheimo, P.; Mattila, T.; Sironen, S.; Myllymaa, T.; Saramäki, K. Construction and demolition waste management—A holistic evaluation of environmental performance. *J. Clean. Prod.* **2015**, *107*, 333–341. [CrossRef]
12. Akhtar, A.; Sarmah, A.K. Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [CrossRef]
13. Peças, P.; Carvalho, V.H.; Salman, H.; Leite, M. Natural Fibre Composites and Their Applications: A Review. *J. Compos. Sci.* **2018**, *2*, 66. [CrossRef]
14. Ardanuy, M.; Claramunt, J.; Toledo Filho, R.D. Cellulosic fiber reinforced cement-based composites: A review of recent research. *Constr. Build. Mater.* **2015**, *79*, 115–128. [CrossRef]
15. Pacheco-Torgal, F.; Jalali, S. Cementitious building materials reinforced with vegetable fibres: A review. *Constr. Build. Mater.* **2011**, *25*, 575–581. [CrossRef]
16. Tian, H.; Zhang, Y.X.; Yang, C.; Ding, Y. Recent advances in experimental studies of the mechanical behaviour of natural fibre-reinforced cementitious composites. *Struct. Concr.* **2016**, *17*, 564–575. [CrossRef]
17. Ahmad, J.; Arbili, M.M.; Majdi, A.; Althoey, F.; Deifalla, A.F.; Rahmawati, C. Performance of concrete reinforced with jute fibers (natural fibers): A review. *J. Eng. Fibers Fabr.* **2022**, *17*, 15589250221121871. [CrossRef]
18. Wang, B.; Bachtiar, E.V.; Yan, L.; Kasal, B.; Fiore, V. Flax, Basalt, E-Glass FRP and Their Hybrid FRP Strengthened Wood Beams: An Experimental Study. *Polymers* **2019**, *11*, 1255. [CrossRef] [PubMed]

19. Yan, L.; Chouw, N. Experimental study of flax FRP tube encased coir fibre reinforced concrete composite column. *Constr. Build. Mater.* **2013**, *40*, 1118–1127. [CrossRef]
20. CoDyre, L.; Fam, A. Axial Strength of Sandwich Panels of Different Lengths with Natural Flax-Fiber Composite Skins and Different Foam-Core Densities. *J. Compos. Constr.* **2017**, *21*, 04017042. [CrossRef]
21. Spierling, S.; Knüpffer, E.; Behnsen, H.; Mudersbach, M.; Krieg, H.; Springer, S.; Albrecht, S.; Herrmann, C.; Endres, H.-J. Bio-based plastics—A review of environmental, social and economic impact assessments. *J. Clean. Prod.* **2018**, *185*, 476–491. [CrossRef]
22. Coutts, R.S.P. A review of Australian research into natural fibre cement composites. *Cem. Concr. Compos.* **2005**, *27*, 518–526. [CrossRef]
23. Ibraheem, S.A.; Ali, A.; Khalina, A. Development of Green Insulation Boards from Kenaf Fibres and Polyurethane. *Polym.-Plast. Technol. Eng.* **2011**, *50*, 613–621. [CrossRef]
24. Fiore, V.; Di Bella, G.; Valenza, A. Effect of Sheep Wool Fibers on Thermal Insulation and Mechanical Properties of Cement-Based Composites. *J. Nat. Fibers* **2019**, *17*, 1532–1543. [CrossRef]
25. Alyousef, R.; Alabduljabbar, H.; Mohammadhosseini, H.; Mohamed, A.M.; Siddika, A.; Alrshoudi, F.; Alaskar, A. Utilization of sheep wool as potential fibrous materials in the production of concrete composites. *J. Build. Eng.* **2020**, *30*, 101216. [CrossRef]
26. Vilaplana, F.; Strömberg, E.; Karlsson, S. Environmental and resource aspects of sustainable biocomposites. *Polym. Degrad. Stab.* **2010**, *95*, 2147–2161. [CrossRef]
27. Mohanty, A.K.; Misra, M.; Drzal, L.T. *Natural Fibers, Biopolymers, and Biocomposites*; Lawrence, T., Ed.; Taylor & Francis: Abingdon upon Thames, UK, 2005; ISBN 9780203508206.
28. Gurunathan, T.; Mohanty, S.; Nayak, S.K. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Compos. Part A Appl. Sci. Manuf.* **2015**, *77*, 1–25. [CrossRef]
29. Aditya, P.; Kishore, K.; Prasad, D. Characterization of Natural Fiber Reinforced Composites. *Int. J. Eng. Appl. Sci.* **2017**, *4*, 26–32.
30. Averous, L.; Boquillon, N. Biocomposites based on plasticized starch: Thermal and mechanical behaviours. *Carbohydr. Polym.* **2004**, *56*, 111–122. [CrossRef]
31. Ramamoorthy, S.K.; Skrifvars, M.; Persson, A. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. *Polym. Rev.* **2015**, *55*, 107–162. [CrossRef]
32. La Mantia, F.P.; Morreale, M. Green composites: A brief review. *Compos. Part A Appl. Sci. Manuf.* **2011**, *42*, 579–588. [CrossRef]
33. Wedin, R. *Chemistry on a High-Carb Diet*; American Chemical Society: Washington, DC, USA, 2004; pp. 23–27.
34. Shanks, R.A.; Hodzic, A.; Wong, S. Thermoplastic biopolyester natural fiber composites. *J. Appl. Polym. Sci.* **2004**, *91*, 2114–2121. [CrossRef]
35. Pandey, J.; Nagarajan, V.; Mohanty, A.K.; Misra, M. Commercial potential and competitiveness of natural fiber composites. In *Biocomposites*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 1–15.
36. Lalit, R.; Mayank, P.; Ankur, K. Natural Fibers and Biopolymers Characterization: A Future Potential Composite Material. *J. Mech. Eng.* **2018**, *68*, 33–50. [CrossRef]
37. Neto, J.S.S.; de Queiroz, H.F.M.; Aguiar, R.A.A.; Banea, M.D. A Review on the Thermal Characterisation of Natural and Hybrid Fiber Composites. *Polymers* **2021**, *13*, 4425. [CrossRef]
38. Townsend, T. 1B—World natural fibre production and employment. In *Handbook of Natural Fibres*; Kozłowski, R.M., Mackiewicz-Talarczyk, M., Eds.; The Textile Institute Book Series; Elsevier WP Woodhead Publishing: Duxford, UK; Cambridge, UK; Kidlington, UK, 2020; pp. 15–36. ISBN 978-0-12-818398-4.
39. Van Dam, J.E.G. Environmental Benefits of Natural Fibre Production and Use. In Proceedings of the Symposium on Natural Fibres. 2020. Available online: https://www.fao.org/3/i0709e/i0709e03.pdf (accessed on 15 July 2021).
40. Campilho, R.D.S.G. Recent innovations in biocomposite products. In *Biocomposites for High-Performance Applications: Current Barriers and Future Needs Towards Industrial Development*; Elsevier: Amsterdam, The Netherlands, 2017; ISBN 9780081007945.
41. Guo, Y.; Deng, Y. Recycling of Flax Fiber Towards Developing Biocomposites for Automotive Application From a Life Cycle Assessment Perspective. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Hoboken, NJ, USA, 2019. [CrossRef]
42. Akampumuza, O.; Wambua, P.M.; Ahmed, A.; Li, W.; Qin, X.-H. Review of the applications of biocomposites in the automotive industry. *Polym. Compos.* **2016**, *38*, 2553–2569. [CrossRef]
43. Khalfallah, M.; Abbès, B.; Abbès, F.; Guo, Y.; Marcel, V.; Duval, A.; Vanfleteren, F.; Rousseau, F. Innovative flax tapes reinforced Acrodur biocomposites: A new alternative for automotive applications. *Mater. Des.* **2014**, *64*, 116–126. [CrossRef]
44. Roy, P.; Tadele, D.; Defersha, F.; Misra, M.; Mohanty, A.K. Environmental and economic prospects of biomaterials in the automotive industry. *Clean Technol. Environ. Policy* **2019**, *21*, 1535–1548. [CrossRef]
45. Guadagnuolo, M.; Faella, G. Simplified Design of Masonry Ring-Beams Reinforced by Flax Fibers for Existing Buildings Retrofitting. *Buildings* **2020**, *10*, 12. [CrossRef]
46. Korjenic, A.; Zach, J.; Hroudová, J. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. *Energy Build.* **2016**, *116*, 45–58. [CrossRef]
47. Bharath, K.N.; Basavarajappa, S. Applications of biocomposite materials based on natural fibers from renewable resources: A review. *Sci. Eng. Compos. Mater.* **2016**, *23*, 123–133. [CrossRef]

48. Grozdanov, A.; Jordanov, I.; Errico, M.; Gentile, G.; Avella, M. Biocomposites Based on Natural Fibers and Polymer Matrix—From Theory to Industrial Products. In *Green Biorenewable Biocomposites*; Apple Academic Press: Palm Bay, FL, USA, 2015.
49. Yılmaz, N.; Powell, N. Biocomposite Structures as Sound Absorber Materials. In *Green Biorenewable Biocomposites*; Apple Academic Press: Palm Bay, FL, USA, 2015. [CrossRef]
50. Sirviö, J.A.; Kolehmainen, A.; Liimatainen, H.; Niinimäki, J.; Hormi, O.E. Biocomposite cellulose-alginate films: Promising packaging materials. *Food Chem.* **2014**, *151*, 343–351. [CrossRef]
51. Marra, A.; Silvestre, C.; Duraccio, D.; Cimmino, S. Polylactic acid/zinc oxide biocomposite films for food packaging application. *Int. J. Biol. Macromol.* **2016**, *88*, 254–262. [CrossRef]
52. Narayanan, M.; Loganathan, S.; Valapa, R.B.; Thomas, S.; Varghese, T. UV protective poly(lactic acid)/rosin films for sustainable packaging. *Int. J. Biol. Macromol.* **2017**, *99*, 37–45. [CrossRef]
53. Annamalai, P.; Depan, D. Nano-Cellulose Reinforced Chitosan Nanocomposites For Packaging and Biomedical Applications. In *Green Biorenewable Biocomposites*; Apple Academic Press: Palm Bay, FL, USA, 2015.
54. Fouly, A.; Ibrahim, A.; Sherif, E.-S.; FathEl-Bab, A.; Badran, A. Effect of Low Hydroxyapatite Loading Fraction on the Mechanical and Tribological Characteristics of Poly(Methyl Methacrylate) Nanocomposites for Dentures. *Polymers* **2021**, *13*, 857. [CrossRef]
55. Fouly, A.; Alnaser, I.A.; Assaifan, A.K.; Abdo, H.S. Evaluating the Performance of 3D-Printed PLA Reinforced with Date Pit Particles for Its Suitability as an Acetabular Liner in Artificial Hip Joints. *Polymers* **2022**, *14*, 3321. [CrossRef] [PubMed]
56. Ilyas, R.A.; Zuhri, M.Y.M.; Norrrahim, M.N.F.; Misenan, M.S.M.; Jenol, M.A.; Samsudin, S.A.; Nurazzi, N.M.; Asyraf, M.R.M.; Supian, A.B.M.; Bangar, S.P.; et al. Natural Fiber-Reinforced Polycaprolactone Green and Hybrid Biocomposites for Various Advanced Applications. *Polymers* **2022**, *14*, 182. [CrossRef] [PubMed]
57. Reddy, T.R.K.; Kim, H.-J.; Park, J.-W. Renewable Biocomposite Properties and their Applications. In *Composites from Renewable and Sustainable Materials*; IntechOpen: London, UK, 2016.
58. Gorz, A. *Ecologica*; Editoriale Jaca Book: Milano, Italy, 2009; Volume 867, ISBN 8816408677.
59. Drury, J. Hemp Hits New High as Building Material on Dutch Bridge. Available online: https://www.reuters.com/article/us-netherlands-biobridge-idUSKBN1522HG (accessed on 12 December 2020).
60. Mathijsen, D. Innovative bio-composite bicycle swing bridge "Ritsumasyl" in the Netherlands shows why the industry should embrace bio-based composites. *Reinf. Plast.* **2020**, *64*, 212–217. [CrossRef]
61. Barbhuiya, S.; Das, B.B. A comprehensive review on the use of hemp in concrete. *Constr. Build. Mater.* **2022**, *341*. [CrossRef]
62. Sáez-Pérez, M.; Brümmer, M.; Durán-Suárez, J. A review of the factors affecting the properties and performance of hemp aggregate concretes. *J. Build. Eng.* **2020**, *31*, 101323. [CrossRef]
63. Jami, T.; Karade, S.R.; Singh, L.P. A review of the properties of hemp concrete for green building applications. *J. Clean. Prod.* **2019**, *239*, 117852. [CrossRef]
64. Fernandez, J.E. Flax fiber reinforced concrete—A natural fiber biocomposite for sustainable building materials. In *High Performance Structures and Materials*; WIT Press: Southampton, UK, 2002.
65. Page, J.; Khadraoui, F.; Boutouil, M.; Gomina, M. Multi-physical properties of a structural concrete incorporating short flax fibers. *Constr. Build. Mater.* **2017**, *140*, 344–353. [CrossRef]
66. Kouta, N.; Saliba, J.; Saiyouri, N. Fracture behavior of flax fibers reinforced earth concrete. *Eng. Fract. Mech.* **2020**, *241*, 107378. [CrossRef]
67. Benmahiddine, F.; Cherif, R.; Bennai, F.; Belarbi, R.; Tahakourt, A.; Abahri, K. Effect of flax shives content and size on the hygrothermal and mechanical properties of flax concrete. *Constr. Build. Mater.* **2020**, *262*, 120077. [CrossRef]
68. Garikapati, K.P.; Sadeghian, P. Mechanical behavior of flax-lime concrete blocks made of waste flax shives and lime binder reinforced with jute fabric. *J. Build. Eng.* **2020**, *29*, 101187. [CrossRef]
69. Rahimi, M.; Hisseine, O.A.; Tagnit-Hamou, A. Effectiveness of treated flax fibers in improving the early age behavior of high-performance concrete. *J. Build. Eng.* **2021**, *45*, 103448. [CrossRef]
70. Li, Z.; Wang, X.; Wang, L. Properties of hemp fibre reinforced concrete composites. *Compos. Part A Appl. Sci. Manuf.* **2006**, *37*, 497–505. [CrossRef]
71. de Bruijn, P.B.; Jeppsson, K.-H.; Sandin, K.; Nilsson, C. Mechanical properties of lime–hemp concrete containing shives and fibres. *Biosyst. Eng.* **2009**, *103*, 474–479. [CrossRef]
72. Arnaud, L.; Gourlay, E. Experimental study of parameters influencing mechanical properties of hemp concretes. *Constr. Build. Mater.* **2012**, *28*, 50–56. [CrossRef]
73. Awwad, E.; Mabsout, M.; Hamad, B.; Farran, M.T.; Khatib, H. Studies on fiber-reinforced concrete using industrial hemp fibers. *Constr. Build. Mater.* **2012**, *35*, 710–717. [CrossRef]
74. Awwad, E.; Choueiter, D.; Khatib, H. Concrete masonry blocks reinforced with local industrial hemp fibers and hurds. In Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies, Kyoto, Japan, 18–21 August 2013.
75. Merta, I.; Tschegg, E. Fracture energy of natural fibre reinforced concrete. *Constr. Build. Mater.* **2013**, *40*, 991–997. [CrossRef]
76. Walker, R.; Pavia, S.; Mitchell, R. Mechanical properties and durability of hemp-lime concretes. *Constr. Build. Mater.* **2014**, *61*, 340–348. [CrossRef]
77. Zhou, X.M.; Madanipour, R.; Ghaffar, S. Impact Properties of Hemp Fibre Reinforced Cementitious Composites. *Key Eng. Mater.* **2016**, *711*, 163–170. [CrossRef]

78. Barbuta, M.; Serbanoiu, A.A.; Teodorescu, R.; Rosca, B.; Mitroi, R.; Bejan, G. Characterization of polymer concrete with natural fibers. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *246*, 012033. [CrossRef]
79. Grubeša, I.N.; Marković, B.; Gojević, A.; Brdarić, J. Effect of hemp fibers on fire resistance of concrete. *Constr. Build. Mater.* **2018**, *184*, 473–484. [CrossRef]
80. Wong, K.; Zahi, S.; Low, K.; Lim, C. Fracture characterisation of short bamboo fibre reinforced polyester composites. *Mater. Des.* **2010**, *31*, 4147–4154. [CrossRef]
81. Zhang, C.; Huang, Z.; Chen, G.W. Experimental research on bamboo fiber reinforced concrete. *Appl. Mech. Mater.* **2013**, *357*, 1045–1048. [CrossRef]
82. Ahmed, S.; Raza, A.; Gupta, H. Mechanical Properties of Bamboo Fibre Reinforced Concrete. In Proceedings of the 2nd International Conference on Research in Science, Engineering and Technology, Dubai, United Arab Emirates, 21–22 March 2014. [CrossRef]
83. Agarwal, A.; Nanda, B.; Maity, D. Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. *Constr. Build. Mater.* **2014**, *71*, 610–617. [CrossRef]
84. Moroz, J.; Lissel, S.; Hagel, M. Performance of bamboo reinforced concrete masonry shear walls. *Constr. Build. Mater.* **2014**, *61*, 125–137. [CrossRef]
85. Goh, L.D.; Zulkornain, A.S. Influence of bamboo in concrete and beam applications. *J. Phys. Conf. Ser.* **2019**, *1349*, 012127. [CrossRef]
86. Sridhar, J.; Gobinath, R.; Kırgız, M.S. Comparative study for efficacy of chemically treated jute fiber and bamboo fiber on the properties of reinforced concrete beams. *J. Nat. Fibers* **2022**, *19*, 1–11. [CrossRef]
87. Dhandhania, V.; Sawant, S. Coir Fiber Reinforced Concrete. *J. Text. Sci. Eng.* **2014**, *4*, 5.
88. Ahmad, W.; Farooq, S.H.; Usman, M.; Khan, M.; Ahmad, A.; Aslam, F.; Al Yousef, R.; Al Abduljabbar, H.; Sufian, M.; Alyousef, R.; et al. Effect of coconut fiber length and content on properties of high strength concrete. *Materials* **2020**, *13*, 1075. [CrossRef]
89. Khan, M.; Rehman, A.; Ali, M. Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road. *Constr. Build. Mater.* **2020**, *244*, 118382. [CrossRef]
90. Elsaid, A.; Dawood, M.; Seracino, R.; Bobko, C. Mechanical properties of kenaf fiber reinforced concrete. *Constr. Build. Mater.* **2011**, *25*, 1991–2001. [CrossRef]
91. Mohsin, S.M.; Baarimah, A.O.; Jokhio, G.A. Effect of kenaf fiber in reinforced concrete slab. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018; Volume 342, p. 012104.
92. Baarimah, A.O.; Syed Mohsin, S.M. Mechanical properties of steel/kenaf (hybrid) fibers added into concrete mixtures. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *342*, 012075. [CrossRef]
93. Muda, Z.C.; Mohd Kamal, N.L.; Syamsir, A.; Sheng, C.Y.; Beddu, S.; Mustapha, K.N.; Thiruchelvam, S.; Usman, F.; Alam, M.A.; Birima, A.H.; et al. Impact Resistance Performance of Kenaf Fibre Reinforced Concrete. *IOP Conf. Ser. Earth Environ. Sci.* **2016**, *32*, 012019. [CrossRef]
94. Mahzabin, M.S.; Jee Hock, L.; Siong Kang, L.; Nikbakht Jarghouyeh, E. Behaviour of kenaf fibre reinforced composite. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2019; Volume 513.
95. Zhou, C.; Cai, L.; Chen, Z.; Li, J. Effect of kenaf fiber on mechanical properties of high-strength cement composites. *Constr. Build. Mater.* **2020**, *263*, 121007. [CrossRef]
96. Hu, B.; Zhang, N.; Liao, Y.; Pan, Z.; Liu, Y.; Zhou, L.; Liu, Z.; Jiang, Z. Enhanced flexural performance of epoxy polymer concrete with short natural fibers. *Sci. China Technol. Sci.* **2018**, *61*, 1107–1113. [CrossRef]
97. Prasannan, D.; Nivin, S.; Kumar, R.R.; Giridharan, S.; Elavivekan, M. Comparative Study of Banana and Sisal Fibre Reinforced Concrete With Conventional Concrete. *Int. J. Pure Appl. Math.* **2018**, *118*, 1757–1765.
98. Frazão, C.; Barros, J.; Filho, R.T.; Ferreira, S.; Gonçalves, D. Development of sandwich panels combining Sisal Fiber-Cement Composites and Fiber-Reinforced Lightweight Concrete. *Cem. Concr. Compos.* **2018**, *86*, 206–223. [CrossRef]
99. Okeola, A.A.; Abuodha, S.O.; Mwero, J. Experimental Investigation of the Physical and Mechanical Properties of Sisal Fiber-Reinforced Concrete. *Fibers* **2018**, *6*, 53. [CrossRef]
100. Mouli, K.C.; Pannirselvam, N.; Anitha, V.; Kumar, D.V.; Rao, S.V. Strength studies on banana fibre concrete with metakaolin. *Int. J. Civ. Eng. Technol.* **2019**, *10*, 684–689.
101. Zakaria, M.; Ahmed, M.; Hoque, M.; Islam, S. Scope of using jute fiber for the reinforcement of concrete material. *Text. Cloth. Sustain.* **2016**, *2*, 123. [CrossRef]
102. Zia, A.; Ali, M. Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining. *Constr. Build. Mater.* **2017**, *155*, 726–739. [CrossRef]
103. Akasaka, H.; Ozawa, M.; Parajuli, S.S.; Sugino, Y.; Akutsu, Y.; Murakami, M. Preventive Effect on Fire Spalling of High-Strength Concrete With Jute Fibre in Ring-Restraint Specimen. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018; Volume 431. [CrossRef]
104. Dayananda, N.; Gowda, B.S.K.; Prasad, G.L.E. A Study on Compressive Strength Attributes of Jute Fiber Reinforced Cement Concrete Composites. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *376*, 012069. [CrossRef]
105. Kundu, S.P.; Chakraborty, S.; Chakraborty, S. Effectiveness of the surface modified jute fibre as fibre reinforcement in controlling the physical and mechanical properties of concrete paver blocks. *Constr. Build. Mater.* **2018**, *191*, 554–563. [CrossRef]
106. Islam, M.S.; Ahmed, S.J. Influence of jute fiber on concrete properties. *Constr. Build. Mater.* **2018**, *189*, 768–776. [CrossRef]

107. Zhang, T.; Yin, Y.; Gong, Y.; Wang, L. Mechanical properties of jute fiber-reinforced high-strength concrete. *Struct. Concr.* **2019**, *21*, 703–712. [CrossRef]
108. Ahmed, S.; Ali, M. Improvement in Impact Resistance of GFRP Rebars Reinforced Concrete Wall Panels Using Jute Fibres. In Proceedings of the 11th International Civil Engineering, Karachi, Pakistan, 13–14 March 2020.
109. Zhang, D.; Tan, K.H.; Dasari, A.; Weng, Y. Effect of natural fibers on thermal spalling resistance of ultra-high performance concrete. *Cem. Concr. Compos.* **2020**, *109*, 103512. [CrossRef]
110. Khaleel, S.; Madhavi, K.; Basutkar, S. Mechanical characteristics of brick masonry using natural fiber composites. *Mater. Today Proc.* **2020**, *46*, 4817–4824. [CrossRef]
111. Irawan, T.; Saloma; Idris, Y. Mechanical Properties of Foamed Concrete with Additional Pineapple Fiber and Polypropylene Fiber. *J. Phys. Conf. Ser.* **2019**, *1198*, 082018. [CrossRef]
112. Esper, C.D.H.; Canseco, H.A.R. Influence of Alkali Treatment and Fiber Content on Mechanical Properties of Pineapple Leaf Fiber (PALF)-Reinforced Cement-Based Composites via Full Factorial Design. *Mater. Sci. Forum* **2020**, *1005*, 65–75. [CrossRef]
113. Onuaguluchi, O.; Banthia, N. Plant-based natural fibre reinforced cement composites: A review. *Cem. Concr. Compos.* **2016**, *68*, 96–108. [CrossRef]
114. Lee, G.-W.; Choi, Y.-C. Effect of abaca natural fiber on the setting behavior and autogenous shrinkage of cement composite. *J. Build. Eng.* **2022**, *56*, 104719. [CrossRef]
115. Voutetaki, M.E.; Naoum, M.C.; Papadopoulos, N.A.; Chalioris, C.E. Cracking Diagnosis in Fiber-Reinforced Concrete with Synthetic Fibers Using Piezoelectric Transducers. *Fibers* **2022**, *10*, 5. [CrossRef]
116. Mwaikambo, L.Y.; Ansell, M.P. Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials. I. hemp fibres. *J. Mater. Sci.* **2006**, *41*, 2483–2496. [CrossRef]
117. Hu, B.; Dweib, M.; Wool, R.P.; Shenton, H.W. Bio-Based Composite Roof for Residential Construction. *J. Arch. Eng.* **2007**, *13*, 136–143. [CrossRef]
118. Takasaki, K.; Jirawattanasomkul, T.; Zhang, D.; Ueda, T. Experimental study on shear behavior of RC beams jacketed by flax fiber sheet. *Proc. Japan Concr. Inst.* **2014**, *36*, 1189–1194.
119. Yan, L.; Su, S.; Chouw, N. Microstructure, flexural properties and durability of coir fibre reinforced concrete beams externally strengthened with flax FRP composites. *Compos. Part B Eng.* **2015**, *80*, 343–354. [CrossRef]
120. Huang, L.; Yan, B.; Yan, L.; Xu, Q.; Tan, H.; Kasal, B. Reinforced concrete beams strengthened with externally bonded natural flax FRP plates. *Compos. Part B Eng.* **2016**, *91*, 569–578. [CrossRef]
121. Di Luccio, G.; Michel, L.; Ferrier, E.; Martinelli, E. Seismic retrofitting of RC walls externally strengthened by flax–FRP strips. *Compos. Part B Eng.* **2017**, *127*, 133–149. [CrossRef]
122. Wang, W.; Chouw, N. Experimental and theoretical studies of flax FRP strengthened coconut fibre reinforced concrete slabs under impact loadings. *Constr. Build. Mater.* **2018**, *171*, 546–557. [CrossRef]
123. Chen, C.; Yang, Y.; Zhou, Y.; Xue, C.; Chen, X.; Wu, H.; Sui, L.; Li, X. Comparative analysis of natural fiber reinforced polymer and carbon fiber reinforced polymer in strengthening of reinforced concrete beams. *J. Clean. Prod.* **2020**, *263*, 121572. [CrossRef]
124. Siriluk, S.; Hussain, Q.; Rattanapitikon, W.; Pimanmas, A. Shear Strengthening of Reinforced Concrete Beams with HFRP Composite. *Mater. Sci. Forum* **2016**, *860*, 152–155. [CrossRef]
125. Ghalieh, L.; Awwad, E.; Saad, G.; Khatib, H.; Mabsout, M. Concrete Columns Wrapped with Hemp Fiber Reinforced Polymer—An Experimental Study. *Procedia Eng.* **2017**, *200*, 440–447. [CrossRef]
126. Bitar, R.; Saad, G.; Awwad, E.; El Khatib, H.; Mabsout, M. Strengthening unreinforced masonry walls using natural hemp fibers. *J. Build. Eng.* **2020**, *30*, 101253. [CrossRef]
127. Sen, T.; Reddy, H.J. Strengthening of RC beams in flexure using natural jute fibre textile reinforced composite system and its comparative study with CFRP and GFRP strengthening systems. *Int. J. Sustain. Built Environ.* **2013**, *2*, 41–55. [CrossRef]
128. Hafizah, N.A.K.; Bhutta, M.A.R.; Jamaludin, M.Y.; Warid, M.H.; Ismail, M.; Rahman, M.S.; Yunus, I.; Azman, M. Kenaf Fiber Reinforced Polymer Composites for Strengthening RC Beams. *J. Adv. Concr. Technol.* **2014**, *12*, 167–177. [CrossRef]
129. Sen, T.; Reddy, H.J. Flexural strengthening of RC beams using natural sisal and artificial carbon and glass fabric reinforced composite system. *Sustain. Cities Soc.* **2014**, *10*, 195–206. [CrossRef]
130. Sen, T.; Paul, A. Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP. *Int. J. Sustain. Built Environ.* **2015**, *4*, 248–264. [CrossRef]
131. Tan, H.; Yan, L.; Huang, L.; Wang, Y.; Li, H.; Chen, J.-Y. Behavior of sisal fiber concrete cylinders externally wrapped with jute FRP. *Polym. Compos.* **2015**, *38*, 1910–1917. [CrossRef]
132. Alam, A.; Al Riyami, K. Shear strengthening of reinforced concrete beam using natural fibre reinforced polymer laminates. *Constr. Build. Mater.* **2018**, *162*, 683–696. [CrossRef]
133. Omar, Z.; Sugiman, S.; Yussof, M.M.; Ahmad, H. The effects of woven fabric Kenaf FRP plates flexural strengthened on plain concrete beam under a four-point bending test. *Case Stud. Constr. Mater.* **2022**, *17*, e01503. [CrossRef]
134. Maulana, M.; Sugiman, S.; Ahmad, H.; Mohd Jaini, Z.; Mansor, H. XFEM Modelling and Experimental Observations of Foam Concrete Beam Externally-Bonded with KFRP Sheet. *Lat. Am. J. Solids Struct.* **2022**, *19*, 460. [CrossRef]
135. Chin, S.C.; Moh, J.N.S.; Doh, S.I.; Yahaya, F.M.; Gimbun, J. Strengthening of Reinforced Concrete Beams Using Bamboo Fiber/Epoxy Composite Plates in Flexure. *Key Eng. Mater.* **2019**, *821*, 465–471. [CrossRef]

136. Tshai, K.Y.; Kong, I. 12-Advancement in flame retardancy of natural fibre reinforced composites with macro to nanoscale particulates additives. In *Woodhead Publishing Series in Composites Science and Engineering*; Goh, K.L., Aswathy, M.K., De Silva, R.T., Thomas, S., Eds.; Woodhead Publishing: Sawston, UK, 2020; pp. 311–342.
137. Yan, B.; Huang, L.; Yan, L.; Gao, C.; Kasal, B. Behavior of flax FRP tube encased recycled aggregate concrete with clay brick aggregate. *Constr. Build. Mater.* **2017**, *136*, 265–276. [CrossRef]
138. Huang, L.; Chen, L.; Yan, L.; Kasal, B.; Jiang, Y.; Liu, C. Behavior of polyester FRP tube encased recycled aggregate concrete with recycled clay brick aggregate: Size and slenderness ratio effects. *Constr. Build. Mater.* **2017**, *154*, 123–136. [CrossRef]
139. Gao, C.; Fu, Q.; Huang, L.; Yan, L.; Gu, G. Jute Fiber-Reinforced Polymer Tube-Confined Sisal Fiber-Reinforced Recycled Aggregate Concrete Waste. *Polymers* **2022**, *14*, 1260. [CrossRef]
140. Betts, D.; Sadeghian, P.; Fam, A. Structural behaviour of sandwich panels constructed of foam cores and flax FRP facings. In Proceedings of the 6th International Conference on Engineering Mechanics and Materials, Vancouver, BC, Canada, 31 May–3 June 2017.
141. Codyre, L.; Mak, K.; Fam, A. Flexural and axial behaviour of sandwich panels with bio-based flax fibre-reinforced polymer skins and various foam core densities. *J. Sandw. Struct. Mater.* **2016**, *20*, 595–616. [CrossRef]
142. Firouzsalari, S.E.; Dizhur, D.; Jayaraman, K.; Ingham, J.M. Bending behaviour of flax fabric-reinforced epoxy pipes. *Compos. Part A Appl. Sci. Manuf.* **2020**, *140*, 106179. [CrossRef]
143. Shah, D.U.; Schubel, P.J.; Clifford, M.J. Can flax replace E-glass in structural composites? A small wind turbine blade case study. *Compos. Part B Eng.* **2013**, *52*, 172–181. [CrossRef]
144. Markiewicz, E.; Borysiak, S.; Paukszta, D. Polypropylene-lignocellulosic material composites as promising sound absorbing materials. *Polimery* **2009**, *54*, 430–435. [CrossRef]
145. Khalina, A.; Zainudin, E.; Faizal, A.R.M.; Jalaluddin, H.; Umar, A.; Syuhada, W. Development of Biocomposite Wall Cladding from Kenaf Fibre by Extrusion Molding Process. *Key Eng. Mater.* **2011**, *471–472*, 239–244. [CrossRef]
146. Panigrahi, S.; Rana, A.; Kushwaha, R.L.; Panigrahy, B.S. *Biodegradable Green Composite Boards for Industrial Application*; SAE Technical Paper 2008-01-2625; SAE International: Warrandale, PA, USA, 2008. [CrossRef]
147. Kremensas, A.; Kairytė, A.; Vaitkus, S.; Vėjelis, S.; Balčiūnas, G. Mechanical Performance of Biodegradable Thermoplastic Polymer-Based Biocomposite Boards from Hemp Shivs and Corn Starch for the Building Industry. *Materials* **2019**, *12*, 845. [CrossRef] [PubMed]
148. Brzyski, P.; Barnat-Hunek, D.; Suchorab, Z.; Łagód, G. Composite Materials Based on Hemp and Flax for Low-Energy Buildings. *Materials* **2017**, *10*, 510. [CrossRef] [PubMed]
149. Costantine, G.; Maalouf, C.; Moussa, T.; Polidori, G. Experimental and numerical investigations of thermal performance of a Hemp Lime external building insulation. *Build. Environ.* **2018**, *131*, 140–153. [CrossRef]
150. Corona, A.; Madsen, B.; Hauschild, M.Z.; Birkved, M. Natural fibre selection for composite eco-design. *CIRP Ann.* **2016**, *65*, 13–16. [CrossRef]
151. Correa, J.P.; Montalvo-Navarrete, J.M.; Hidalgo-Salazar, M.A. Carbon footprint considerations for biocomposite materials for sustainable products: A review. *J. Clean. Prod.* **2018**, *208*, 785–794. [CrossRef]
152. *ISO 14040:2006*; Environmental Management. Life Cycle Assessment. Principles and Framework. International Organisation for Standardisation: Geneva, Switzerland, 2006.
153. *BS ISO 15686-5:2017*; Buildings and Constructed Assets—Service Life Planning Part 5: Life-Cycle Costing. International Organisation for Standardisation: Geneva, Switzerland, 2017.
154. de Beus, N.; Carus, M.; Barth, M. Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material. 2019. Available online: http://eiha.org/media/2019/03/19-03-13-Study-Natural-Fibre-Sustainability-Carbon-Footprint.pdf (accessed on 15 June 2021).
155. Dissanayake, N.P.J.; Summerscales, J.; Grove, S.M.; Singh, M.M. Energy Use in the Production of Flax Fiber for the Reinforcement of Composites. *J. Nat. Fibers* **2009**, *6*, 331–346. [CrossRef]
156. Korol, J.; Burchart-Korol, D.; Pichlak, M. Expansion of environmental impact assessment for eco-efficiency evaluation of biocomposites for industrial application. *J. Clean. Prod.* **2016**, *113*, 144–152. [CrossRef]
157. Bhardwaj, S.; Engg, C.S.O.B. Natural Fibre Composites- An Opportunity for Farmers. *Int. J. Pure Appl. Biosci.* **2017**, *5*, 509–514. [CrossRef]
158. Dittenber, D.B.; GangaRao, H.V. Critical review of recent publications on use of natural composites in infrastructure. *Compos. Part A Appl. Sci. Manuf.* **2012**, *43*, 1419–1429. [CrossRef]
159. Korol, J.; Hejna, A.; Burchart-Korol, D.; Chmielnicki, B.; Wypiór, K. Water Footprint Assessment of Selected Polymers, Polymer Blends, Composites, and Biocomposites for Industrial Application. *Polymers* **2019**, *11*, 1791. [CrossRef]
160. Sathishkumar, S.; Naveen, T.K.; Jeevarathinam, A.; Karthik, V.; Dhandapani, N.V. Thermal Conductivity of Natural Fiber Reinforced Plastics. 2018, Volume 118, No. 20. pp. 43–51. Available online: http://www.ijpam.eu (accessed on 19 September 2022).
161. Batouli, S.M.; Zhu, Y. Comparative Life-Cycle Assessment Study of Kenaf Fiber-Based and Glass Fiber-Based Structural Insulation Panels. In Proceedings of the International Conference on Construction and Real Estate Management 2013, ICCREM, Karlsruhe, Germany, 10–11 October 2013; pp. 377–388. [CrossRef]

162. Zea Escamilla, E.; Wallbaum, H. Environmental Savings from the use of Vegetable Fibres as Concrete Reinforcement. In Proceedings of the Modern Methods and Advances in Structural Engineering and Construction, Zurich, Switzerland, 21–26 June 2011; ISBN 978-981-08-7920-4.
163. Arrigoni, A.; Pelosato, R.; Melià, P.; Ruggieri, G.; Sabbadini, S.; Dotelli, G. Life cycle assessment of natural building materials: The role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. *J. Clean. Prod.* **2017**, *149*, 1051–1061. [CrossRef]
164. Díaz, A.V.; López, A.F.; Bugallo, P.M.B. Analysis of Biowaste-Based Materials in the Construction Sector: Evaluation of Thermal Behaviour and Life Cycle Assessment (LCA). *Waste Biomass Valorization* **2022**, *13*, 4983–5004. [CrossRef]
165. Le Duigou, A.; Baley, C. Coupled micromechanical analysis and life cycle assessment as an integrated tool for natural fibre composites development. *J. Clean. Prod.* **2014**, *83*, 61–69. [CrossRef]
166. Merta, I.; Mladenovič, A.; Turk, J.; Šajna, A.; Pranjić, A.M. Life Cycle Assessment of Natural Fibre Reinforced Cementitious Composites. *Key Eng. Mater.* **2018**, *761*, 204–209. [CrossRef]
167. Khoshnava, S.M.; Rostami, R.; Ismail, M.; Rahmat, A.R. A cradle-to-gate based life cycle impact assessment comparing the KBF w EFB hybrid reinforced poly hydroxybutyrate biocomposite and common petroleum-based composites as building materials. *Environ. Impact Assess. Rev.* **2018**, *70*, 11–21. [CrossRef]
168. Xu, X.; Jayaraman, K.; Morin, C.; Pecqueux, N. Life cycle assessment of wood-fibre-reinforced polypropylene composites. *J. Mater. Process. Technol.* **2008**, *198*, 168–177. [CrossRef]
169. Kim, S.; Dale, B.E.; Drzal, L.T.; Misra, M. Life Cycle Assessment of Kenaf Fiber Reinforced Biocomposite. *J. Biobased Mater. Bioenergy* **2008**, *2*, 85–93. [CrossRef]
170. Akhshik, M.; Panthapulakkal, S.; Tjong, J.; Sain, M. Life cycle assessment and cost analysis of hybrid fiber-reinforced engine beauty cover in comparison with glass fiber-reinforced counterpart. *Environ. Impact Assess. Rev.* **2017**, *65*, 111–117. [CrossRef]
171. Haylock, R.; Rosentrater, K.A. Cradle-to-Grave Life Cycle Assessment and Techno-Economic Analysis of Polylactic Acid Composites with Traditional and Bio-Based Fillers. *J. Polym. Environ.* **2017**, *26*, 1484–1503. [CrossRef]
172. Rodriguez, L.J.; Orrego, C.E.; Ribeiro, I.; Peças, P. Life-Cycle Assessment and Life-Cycle Cost study of Banana (Musa sapientum) fiber Biocomposite materials. *Procedia CIRP* **2018**, *69*, 585–590. [CrossRef]
173. Beigbeder, J.; Soccalingame, L.; Perrin, D.; Bénézet, J.-C.; Bergeret, A. How to manage biocomposites wastes end of life? A life cycle assessment approach (LCA) focused on polypropylene (PP)/wood flour and polylactic acid (PLA)/flax fibres biocomposites. *Waste Manag.* **2018**, *83*, 184–193. [CrossRef] [PubMed]
174. Akil, H.M.; Omar, M.F.; Mazuki, A.A.M.; Safiee, S.; Ishak, Z.A.M.; Abu Bakar, A. Kenaf fiber reinforced composites: A review. *Mater. Des.* **2011**, *32*, 4107–4121. [CrossRef]
175. Wambua, P.; Ivens, J.; Verpoest, I. Natural fibres: Can they replace glass in fibre reinforced plastics? *Compos. Sci. Technol.* **2003**, *63*, 1259–1264. [CrossRef]