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sustainability

Review

A Life Cycle Engineering Perspective on Biocomposites as a Solution for a Sustainable Recovery

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Abstract: Composite materials, such as carbon fibre reinforced epoxies, provide more efficient structures than conventional materials through light-weighting, but the associated high energy demand during production can be extremely detrimental to the environment. Biocomposites are an emerging material class with the potential to reduce a product's through-life environmental impact relative to wholly synthetic composites. As with most materials, there are challenges and opportunities with the adoption of biocomposites at the each stage of the life cycle. Life Cycle Engineering is a readily available tool enabling the qualification of a product's performance, and environmental and financial impact, which can be incorporated in the conceptual development phase. Designers and engineers are beginning to actively include the environment in their workflow, allowing them to play a significant role in future sustainability strategies. This review will introduce Life Cycle Engineering and outline how the concept can offer support in the Design for the Environment, followed by a discussion of the advantages and disadvantages of biocomposites throughout their life cycle.

Keywords: circular economy; composite product design; end of life; industrial applications; sustainable composites

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1. Introduction

1.1. Synthetic and Bio-Based Composites

Fibre reinforced polymer composites have been pursued as light-weighting solutions for commercial industries for decades, with their versatility and specific properties offering valuable technical advantages over traditional engineering materials, such as steel or aluminium. They allow for more freedom in design with complex geometries and can embed multi-functionality, such as noise, vibration and harshness (NVH) damping, electromagnetic shielding and fire retardancy. Whilst limited by current design criteria (see, e.g., [1]), the high strength-to-weight ratio offered by composites gives the potential to significantly reduce environmental impact (EI) for applications, such as transport, by enabling products with reduced weight, resulting in lower fuel consumption. Additional durability, achieved through environmental and corrosion resistance, provides extended use life for components too [2]. In the UK alone, the composite market was expected to increase to around GBP 10 billion by 2030 (from just under GBP 2.5 billion in 2015), with the fastest growing industries being automotive, aerospace, renewable energy, and construction [3]. However, Composites Germany have reported that the first half of 2020 saw a severe downturn in ratings due to the impact of the coronavirus pandemic on numerous business segments and areas of application [4]. Even so, an increase in the global production of composites is to be expected, especially with respect to the growing market in renewable energy.

Glass fibre is the most popular reinforcement on the European market by production weight, followed by carbon fibre—both are considered composites of "synthetic" origin (i.e., that both the fibre reinforcement and polymer matrix are manufactured and ultimately derived from petroleum distillates or mineral deposits) [5,6]. Unfortunately, the embodied energy of petroleum or mineral-based materials can be extremely high, and recycling at end of life (EOL) is not straightforward [7]. As concerns over the changing natural environment due to anthropological climate change are becoming more urgent, producers and consumers have been moving towards composites produced from so-called "greener" materials [8]. The Sustainable Recovery plan has been devised by the International Energy Agency in response to the coronavirus pandemic crisis, proposing a "return to business" with sustainable development goals at the core, ensuring longer-term growth and future-proofing jobs [9]. The plan spans over six key areas, including electricity, transport, industry, buildings, fuels and emerging low-carbon technologies—the transition of all of these could be facilitated by a greater integration of composite technology and, potentially, biocomposites.

For the purposes of this review, a clear distinction is made between composites of synthetic or bio-based materials:

- Biocomposites (BCs) is the umbrella term for composites with either reinforcement or matrix derived from natural sources, or both of them (full BC) [10].
- Natural Fibre Reinforced Polymer (NFRP) composites use natural fibre reinforcements derived from plants, animals and geological processes paired with a synthetic matrix.
- Fibre Reinforced Bio-Polymer (FRBP) composites have a synthetic fibre reinforcement with a partially or fully bio-derived matrix.
- Fibre Reinforced Polymer (FRP) composites constitute a fully synthetic fibre reinforcement and matrix, and represent the most established composite combination currently available on the market.

The benefits of adopting BCs over FRP composites are evident within the academic literature. They are produced from naturally-renewable and abundant precursor feedstocks, and possess properties equivalent, on a weight basis, to their synthetic counterparts. Whilst they are potentially biodegradable at the end of their service lives, it is important to note that composites containing bio-based constituents will not guarantee biodegradability, a topic covered in more detail in the work of Sahari and Sapuann [11]. Despite this, their market uptake has been limited to date, and this review presents the challenges to commercialisation and explores promising opportunities for design with greener materials within the composites industry.

1.2. Understanding Environmental Impact

Engineers, designers, manufacturers and researchers are increasingly turning to Life Cycle Assessment (LCA) as an environmental impact analysis method to clearly communicate the advantages of BCs over FRPs. This is a holistic approach that captures material input and waste output information along the whole life cycle of a product system. These inventory data are characterised through a range of scientific techniques to determine the causal impact of that system on the environment and human health. Figure 1 shows the successive life cycles of a representative BC and FRP composite products within a Sustainable Recovery context.

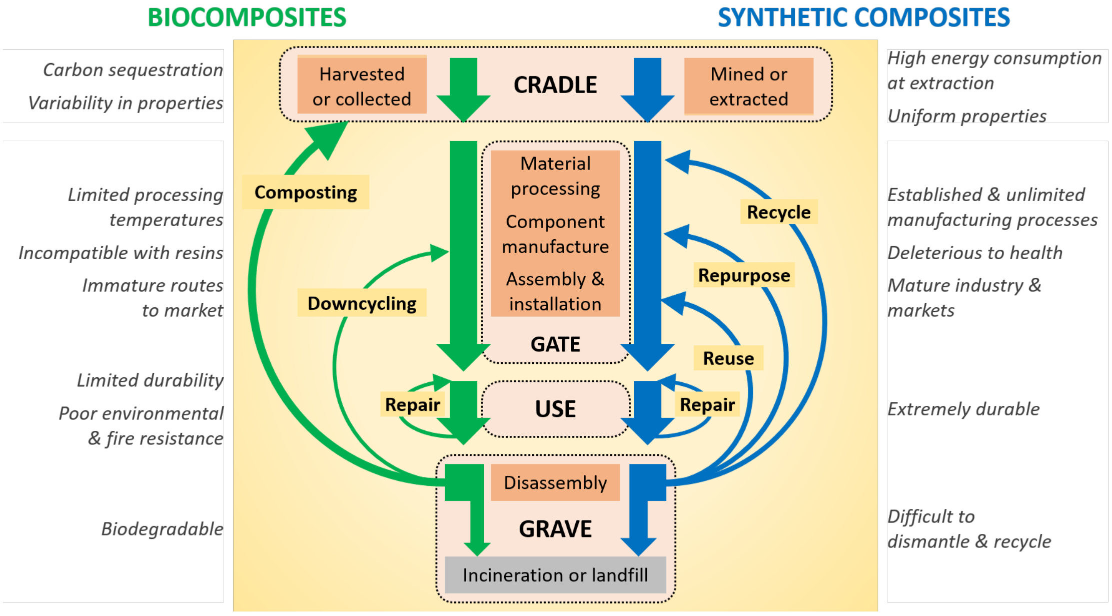

Figure 1. Mapping of design solutions within the life cycle framework of bio-based and synthetic composites to promote the adoption of the circular economy paradigm [12] for sustainable recovery. The central flow diagram summarises the main processing steps from cradle to grave. The flow arrows indicate the path's material retention within the value chain. The notable characteristics at each life cycle stage of the two composite classes are listed on each respective side.

Published LCAs, available for BCs, conclude that the addition of natural fibres to replace all or part of the synthetic fibres demonstrates a reduced EI for that component [13–19]. It has been reported that NFRPs consume around 63% less energy than glass fibre reinforced polymers (GFRPs) during their entire life cycle [19]. Whilst this provides a strong justification to consider selecting bio-based materials, there are other limitations that must be accounted for when replacing traditionally-used synthetic counterparts. Commercially, BCs are currently produced at a small scale and, therefore, the process is not always fully optimised. Sometimes the EI of the BC can be higher than traditional composites, as will be discussed in this paper.

1.3. Life Cycle Engineering

Historically, design engineers have seldom needed to consider the environment during material selection; the two main constraints that have typically driven design decisions are technical performance and cost. The introduction of LCA has provided designers with the ability to gather and model detailed information regarding the EI of a product system earlier in its conceptual development, and incorporate this information in the design process. Life Cycle Engineering (LCE), commonly known as life cycle design, is a method which considers a product's EI over a products life cycle, alongside conventional factors, such as technical performance. LCE has been defined as: *"engineering activities which include the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimising the product life cycle and minimising pollution and waste"* [20].

To demonstrate an application of LCE, previous composite studies have considered flax and glass fibre reinforcements with an epoxy matrix [21–23]. Carvalho et al. applied an LCE framework to a structural component for a mountain bike, evaluating mechanical performance alongside a life cycle environmental and cost analysis to produce four components with epoxy resin and four unique fibre reinforcements: ramie, jute, E-glass and T300 carbon [22]. The incumbent aluminium component had both the lowest mass—symbolising superior mechanical performance—and lowest cost by approximately a third, but had five times the EI. Aluminium's advantageous technical performance, yet more damaging environmental profile, characterises the *"business as usual"* approach, which has contributed to the current climate emergency [24].

The ternary diagram displaying the relative performance of three parameters of synthetic and bio-based polymers shown in Figure 2 has been used to illustrate LCE analysis output [22]. Young's Modulus was used for the technical parameter, and global production capacity for the economic parameter (scaled to include only the polymers within the study group) [25]. The environmental parameter was calculated from a summation of the rankings against energy requirements and a measure of the extent to which the polymer is biodegradable. A polymer's biodegradability is represented as green for high and red for low. This graphical result provides a clear visualisation of each perspective, with each of the three shaded segments within the triangle determining the range of subjective importance (or weight) given to each parameter. The central point of the segments represents a theoretical standpoint of a designer who emphasises 40% on the environment and 30% for both economic and technical factors. A caveat for this type of analysis is the subjective accuracy of data: production capacity was considered for the economic section instead of cost per kg in order to prevent biopolymers from achieving a much lower economic performance score. This figure is not intended as an accurate assessment, rather a representation of the LCE framework and, whilst this output is still highly qualitative, further research is underway to provide more quantitative data to composite designers to achieve a greater understanding of the real-world challenges for larger BC uptake [26].

Biodegradable (🟢)	**Non-Biodegradable (🔴)**
1 - PBS	4 - PE
2 - PLA	5 - PA66
3 - PHA	6 - PET
	7 - PP

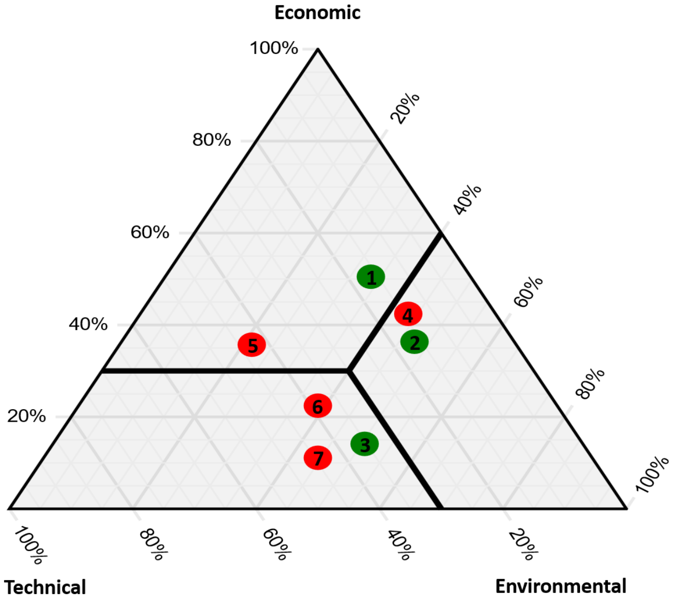

Figure 2. Illustrative LCE assessment of biopolymers. PBS—Polybutylene succinate, PLA—Polylactic acid, PHA–Polyhydroxyalkanoates, PE—Polyethylene, PA66—Nylon 66, PET—Polyethylene terephthalate, PP—Polypropylene [25,27–30].

Following the life cycle succession framework from Figure 2, the extent to which BCs can effectively replace FRPs will be discussed from an LCE perspective, starting with the product design, then production through to EOL. Design is not usually included in a typical LCA of a product but, since this is where the EI is set, it will have a dedicated section herein.

2. Design

Product lifetime, material types and even waste disposal scenarios will all affect a product's EI and a number of impact reduction strategies are available during the design stage. Bio-based reinforcements and resins, outlined in Sections 3.1 and 3.2, may be considered by a designer given their lower greenhouse gas (GHG) emissions per kg of material produced [18,31]. BCs have encountered issues around their technical characteristics when compared with synthetic counterparts, in particular surrounding the lack of macro-scale design, build and test (DBT) experience. A recent review noted that 765 journal papers have been published on the behaviour at laminate scale of composites with some degree of bio-incorporation, and only four of these studies were at the structural level [32]. In practical terms, this lack of structural-scale data will limit development of BCs at the lower technology readiness levels (TRL) of between one and five. However, there have been notable instances of industry utilising BCs, as showcased in Figure 3. BCs, such as those outlined, are finding novel industrial applications in agressive environments, such as quicker and more complete burn-up on re-entry for use on satellite panels, shown in Figure 3c.

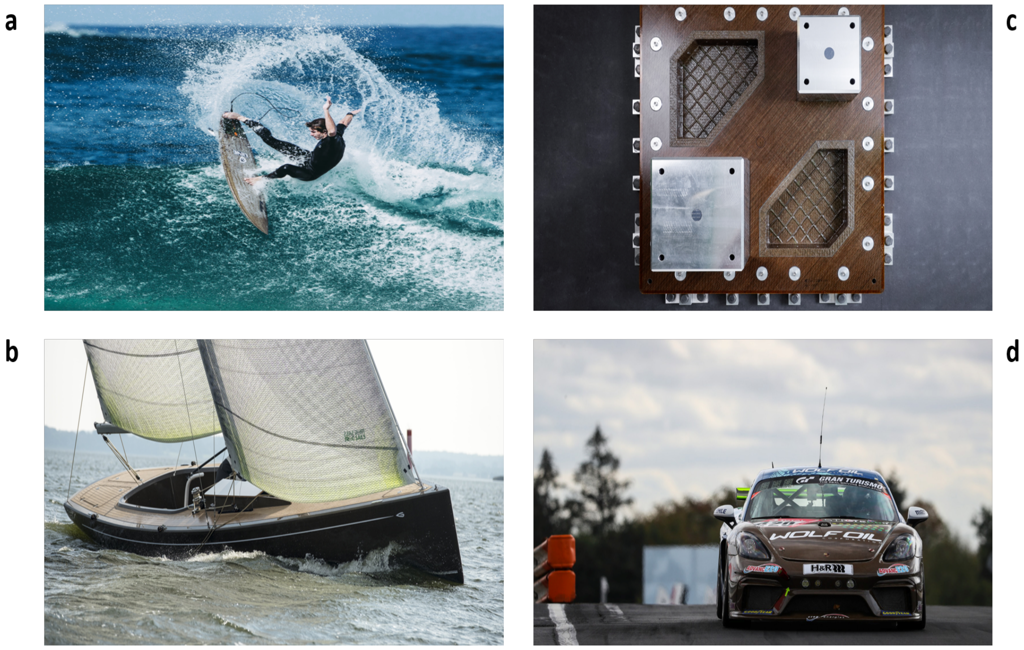

Figure 3. Current industrial applications of BCs ranging from marine to space sectors. (**a**) NOTOX Nshape Pro board constructed with EPS foam, flax and bio-epoxy resin © 2020 Surfer: Liam O'Brien, Photographer: Simon "Swilly" Williams, Published by: Tracks Magazine (Reproduced with permission) (**b**) Greenboats FLAX27 daysailer constructed with ampliTex TM flax fibres and bio-based resin system © Greenboats (Reproduced with permission) (**c**) Flax composite satellite panel © Bcomp (Reproduced with permission) (**d**) Full natural fibre bodywork kit on Porsche Cayman 718 GT4 CS MR © 2020 Dr. Ing. h.c F. Porsch AG (Reproduced with permission).

Within the few structural papers published, wind turbine blades have been discussed and are commonly identified as a potential application for BCs. They are currently manufactured from a wide variety of materials, but primarily from a mixture of GFRP composites and core materials [33,34]. The performance of a 3 m turbine blade manufactured from flax/epoxy (NFRP) and traditional glass/epoxy (FRP) have been compared [35]. The observed flax/epoxy blade's non-linear response was a significantly larger flap-wise deflection relative to the glass/epoxy blade. To avoid blade/tower collision, the NFRP blade would require more reinforcement to provide equivalent bending resistance to the FRP blade, and this additional material and processing requirement implies additional EI. This was also only a 3 m demonstrator and, with blades now reaching 100 m in length, significant work must be done before BC turbine blades can become a reality. Simply because flax fibre emits less carbon dioxide per kg of raw material production than glass fibre does not automatically guarantee that it will make a more environmentally benign product, highlighting the importance of completing a comprehensive cradle-to-cradle LCA before a product can be labelled *"sustainable"*. Large scale applications of BCs in the marine sector include a 4.6 m long boat constructed with flax/epoxy and a balsa wood core. It is reported that the boat has been sailed on numerous occasions with no signs of failure. Greenboats have also released their FLAX27 day-sailing boat, manufactured using BCOMP flax-based materials. These are promising structural applications of BCs and it is hoped they will motivate more academic research in this sector.

Conducting full-scale structural tests to provide confidence in design is an expensive and time-consuming task. The first logical step to improve confidence in design with BCs would be to focus on large-scale simulations, replacing expensive testing with lower-cost models, as proposed by the composite testing pyramid [36]. This has been achieved with large-scale non-linear glass fibre/epoxy FRP composite simulations, providing a body of evidence with which designers can work confidently [37]. To date, only two papers have been published that simulate BC structures: one modelled low-impact velocity testing of hemp or glass/hemp thermoset composites [38] and the other investigated structural response in luffa NFRP composite [39]. This lack of data is currently blocking the wider industry uptake of bio-based materials for composites. More research is urgently required to foster increased designer confidence, in particular, a simulation of wind turbine blade behaviour, similar to work that has been completed on more traditional composites [34,40].

Designing with EOL scenarios in mind has become particularly prevalent as images of waste wind turbine blade graveyards are now a common and undesired consequence for the composites industry [41]. To prevent the loss of material from a technical product system at the end of its service life, the EU Waste Hierarchy regulates the order of preferential waste treatment [42]. EOL treatment should be considered during the design phase, with the aspiration to repurpose and reuse the component, preventing the least-desirable waste treatment options, such as landfill and incineration. Disposal at EOL can have a significant effect on EI. Design for X (DfX) is a design ethos, whereby X can have multiple definitions, ranging from Recycling to Serviceability. Within the available definitions, there are three which cover EOL processes, in order of descending desirability:

- Design for Reuse (DfRu)—Using and re-using a component for its originally intended application for as long as safely possible through repairs and maintenance checks. Fatigue behaviour and repair studies, both key to DfRu, are not discussed in the literature in the context of NFRPs. Whilst the fatigue behaviour of only FRPs is discussed in the literature, the repair of FRPs and BCs is seldom covered for either composite type. A reason for this could be due to the rate of natural degradation of bio-based composite materials, which may render them less fit for purpose at the EOL stage, limiting their options in DfRu.
- Design for Repurpose (DeRp)—Repurposing a structure for a secondary role, with the least amount of processing and transportation possible to minimise the EI. This has been limited to predominantly low TRL demonstrators to date, although there has been some success with repurposing EOL wind turbine blades into urban furniture. WindEurope recently reported DfRp as unlikely to be a large-scale solution for the accumulating amount of composite blade waste [33].
- Design for Recycle (DfRc)—Traditionally, DfRc involves an active consideration of how materials will be compatible with recycling processes, such as grinding or pyrolysis. However, biodegradable BC materials should naturally decay significantly faster than their synthetic non-biodegradable counterparts when composted [43], For example, the common biopolymer polylactic acid (PLA) will degrade when composted in a humidity and temperature-controlled environment. Degrading back to raw implies that the materials will return to the biosphere naturally, circulating the nutrients to prepare for new feedstock, which is not DfRc in the traditional industrial sense, as shown in Figure 1.

Figure 4 shows the corresponding DfX EOL methods which are applicable to composites from bio-based and synthetic (or petroleum-based) materials. As discussed in the technical report by EuCIA Wind, EOL options for synthetic fibres, such as solvolysis, are nearly commercially ready at higher TRL [33]. By contrast, EOL methods for BCs, such as composting, are at a much lower TRL.

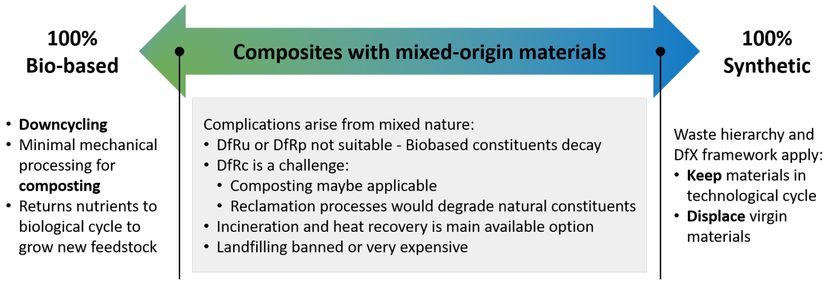

Figure 4. Continuum of composite material origin and the options available at EOL compared with the traditional Waste Hierarchy framework.

A multi-institution project, Re-wind, is investigating the EOL challenge presented by wind turbine blades. The project has produced publications and conference papers discussing DfRu, DfRp and DfRc [44,45], and has recently published a structural analysis of a wind turbine section re-purposed as a residential house roof, showing the proposed design could meet application specified limitations.

An LCA study of flax/PLA BC concluded that mechanical recycling has the least damaging EI, with the carbon dioxide released during composting ranking it worse than recycling for global warming potential [46]. The use of mechanical recycling limits the next life cycle of the composite to manufacturing by injection moulding. Owing to the drop in mechanical properties, relative to continuously reinforced composites, opportunities for application are likely to be limited to secondary and tertiary engineering structures, thus reducing the value of the recycled composite. An example market could be the windsurfing or surfing industry, where the composite from the main surfboard could be ground into recyclate and implemented in to an injection-moulded fin, as demonstrated with epoxy by Starboard and the Maui Fin Company (MFC) [47]. In theory, a flax/epoxy BC could complete its first use phase as the FLAX27 day-sailer; then, at EOL, the reclaimed material can be sent to MFC for fin remanufacture.

3. Available Constituent Materials

Composite are produced by combining two or more constituent materials, with significantly different properties, to create a material of superior characteristics than the individual constituents. FRP composites are typically made of two components: (i) fibres that are responsible for carrying the load and (ii) a matrix that binds the fibres together, distributing the load, providing a rigid shape and protecting the reinforcement from environmental effects. The interface between the fibre and matrix has an important role in the performance of the resultant composite [48]. The mechanical proprieties of the composite are estimated through the summation of constituent properties weighted according to their volume fractions. Failure behaviour is also influenced by the fibre-matrix bonding properties, quantified by the interfacial shear strength (IFSS). This section considers some of the options available for BC materials.

3.1. Natural Fibres

The term "natural fibres" include fibres of organic origin, i.e., plants and animals, or inorganic, i.e., minerals (Figure 5). Organic natural fibres are differentiated by their main unit, cellulose for plant fibres, and proteins for animal fibres. Plants represent the most diverse source of natural fibre: sources include the stems, leaves and fruits of most plants [49].

3.1.1. Plant Fibres

Plant fibres in the bast group (including flax [50,51], hemp [52,53], jute [53,54], kenaf [55,56] and sisal [53,57]) have seen both increased research interest and commercial application in recent years [58,59]. They display specific mechanical properties and added functionality comparable to traditionally-used synthetic fibres, such as glass, as shown in

Tables 1 and 2. The carbon sequestration at production and the potential for energy recovery properties at EOL and their potentially low cost contribute to their sustainability. Reduced dermal and respiratory irritation, together with reduced tool wear during processing can further drive down their EI [60,61]. The mechanical properties of plant fibres are dictated by microfibril orientation, crystallinity and the microstructure, which is influenced by their composition, i.e., the relative amounts of cellulose, hemicellulose, lignin, and sometimes pectin and wax [62]. As seen in Table 2, the range of tensile modulus and strength displayed by different plant fibre types is considerable. Additionally, the age of the plant, climatic conditions and fibre production processes may lead to variability in the properties between fibres of the same type [63]. Owing to the presence of multiple alcoholic hydroxyl groups in the cellulose polymer, plant fibres are hydrophilic and can display significant moisture uptake, reducing most of the mechanical properties due to the plasticisation of the chains and dimensional change within the fibre cell [64]. This can also present a problem with respect to the interface between fibre and matrix, and it is often necessary to introduce a compatibiliser in addition to pre-conditioning the fibres [65], discussed further in Section 3.3. The majority of plant fibres produced are relatively short but can be used in place of discontinuous reinforcements, and in combination with, for example, reclaimed carbon fibres to achieve specific functional properties [66]. Continuous fibres can be produced through traditional spinning techniques or more robust chemical techniques can be used to produce fibres such as viscose rayon, also a potential composite reinforcement [67].

Table 1. Advantages and disadvantages of natural and glass fibres through life cycle stages: cradle, gate, use, grave.

	NATURAL FIBRES	GLASS FIBRES
STAGE	**ADVANTAGES**	
Cradle	High specific mechanical properties Abundant Potentially low cost Renewable Carbon sequestration Low energy consumption	High specific mechanical properties Abundant Low cost Non-corrosive
Gate	Low emission Low energy consumption Non-abrasive	Well-established industry Streamlined process
Use	Extremely lightweight Non-deleterious to health Good insulator	Durability Lightweight High operating temperatures
Grave	Low emission Low energy consumption Compostable Biodegradable	
STAGE	**DISADVANTAGES**	
Cradle	Immature supply chain Moisture absorption	Non renewable Deleterious to health
Gate	Moisture absorption Incompatibility with matrices Limited processing temperatures Abrasive	Deleterious to health High emissions High energy consumption
Use	Large variability of properties Moisture absorption Limited processing/service temperatures Durability Flame resistance	Deleterious to health Poor insulator
Grave		Difficult to recycle Non-biodegradable

3.1.2. Fibres of Animal Origin

Animal-derived fibres also come under the category of natural fibres and have the potential to contribute to the list of possible reinforcements. Processed animal fur and silk are biodegradable materials and are well-established, but production quantities are relatively limited—such fibres are expensive and mainly directed at the textile industry for their comfort and thermal properties [68]. In an attempt to develop a more sustainable composite, a wool by-product from sheep farming was impregnated with a bio-derived resin, producing furniture and household items [69]. Certain spider draglines have a strength and stiffness comparable with carbon fibre, with an elongation to failure of up to 35%, which increases with strain rate, and a toughness higher than aramid fibre and steel [70,71]. Even though these properties are well-known and suggest great engineering potential, the farming of spiders for in vivo spinning is not currently feasible and farming for production of industrially significant quantities is logistically unrealistic. Despite the technical challenges in replicating the natural process [72] there has been extensive biomimetic research to produce engineered fibres either using spider silk protein [73] or non-protein sources [74]; however, these would be simply bio-inspired synthetic and not bio-derived fibres, and as such the environmental benefits may be compromised. In addition, scale up has been limited: a fundamental point with respect to the fibrisation of material is that it eliminates defects. It is still to be determined what would happen to the properties of spider silk if the fibres would be manufactured on the same scale as glass and carbon.

3.1.3. Mineral Fibres

Natural fibres can also be obtained from abundant minerals. Even though they are not regularly considered as bio-based, mineral fibres are the product of the direct transformation of a naturally-occurring resource without further chemicals or additives required to produce the final fibre product. For example, basalt fibres (BFs) are drawn from molten igneous volcanic rocks through an energy-efficient process, requiring lower labour input than the synthetic fibre material extraction processes [75]. Despite a higher production cost per kg than glass fibre, BFs exhibit enhanced specific mechanical and physical properties, such as fire resistance, chemical inertness, low humidity absorption, vibration and acoustic insulation [76]. BFs are significantly lower in cost than carbon fibres and have become a popular novel, lower impact material when used with glass fibres in hybrid composites [75]. They have also been used in hybrid basalt/jute BCs to improve the mechanical, physical and thermal stability properties of the plant-based jute fibre BCs [77]. Owing to their thermal properties, BF reinforced thermoplastics have been patented as protective fire barrier materials [78]. Furthermore, BF composite rebar have been applied in civil engineering applications as a lower EI alternative to steel reinforcement for concrete [79]. Inman et al. have shown that BF composite rebar, compared with conventional steel rebar in concrete beams, are stronger and lighter with a better environmental profile, verified by LCA [80]. Kammeny Vek, a BF producer, compared basalt and glass fibres with woven fabrics through LCA demonstrating the advantages of basalt fibres [81]. Whilst the incorporation of BF offers some environmental advantages, independent environmental assessments, i.e., LCA, with raw data collection are urgently needed to verify BF inclusion over synthetic counterparts and to contribute to the extremely limited pool of current environmental data available in the literature for BFs.

Table 2. Mechanical properties of natural and synthetic fibres.

	Stiffness (GPa)	Tensile Strength (MPa)	Failure Strain (%)	Density (g cm^{-3})	Specific Stiffness (GPa cm^3 g^{-1})	Specific Strength (MPa cm^{3}g^{-1})	Ref.
Natural Fibres							
Plant Fibres							
Flax	40–105	370–1480	1.2–3.3	1.38–1.54	26–76	240–1070	[58,82]
Hemp	24–90	270–900	1.0–3.5	1.20	20–75	225–750	[59]
Sisal	10–40	540–720	2.2–3.3	1.30–1.60	6.3–31	340–550	[59]
Jute	12–60	610–780	1.0–1.9	1.30–1.50	8–46	410–600	[59]
Banana	12	500	4.5–6.5	1.00–1.50	8–12	330–500	[59]
Kenaf	15–53	223–930	9.1–12.3	1.20–1.40	11–44	160–775	[59]
Ramie	1–83	180–1630	1.6–14.5	1.00–1.55	0.6–83	115–1630	[59]
Curaua	12–50	540–1400	3.0–4.3	1.40–1.50	8.4–36	360–1000	[58,82]
Animal Fibres							
Spider Silk	2–21	750–1840	17–52	1.32–1.35	1.5–16	550–1400	[83–85]
Silkworm Silk	1–16	175–1400	4–34	1.34	0.8–12	130–1050	[83,85]
Wool	0.5–2	170–200	5–35	1.30	0.4–1.5	130–155	[83,86]
Mineral Fibres							
Basalt fibres	93–110	3000–4840	3.1–6.0	2.63–2.80	33–42	1050–1850	[76]
Synthetic Fibres							
Glass	72–76	3100–3800	4.7	2.54–2.57	28–30	1200–1500	[76]
Aramid	70–140	2900–3450	2.8–3.6	1.45	48–97	2000–2400	[76]
Carbon	230–600	3500–6000	1.5–2.0	1.78–1.95	120–340	1800–3400	[76]

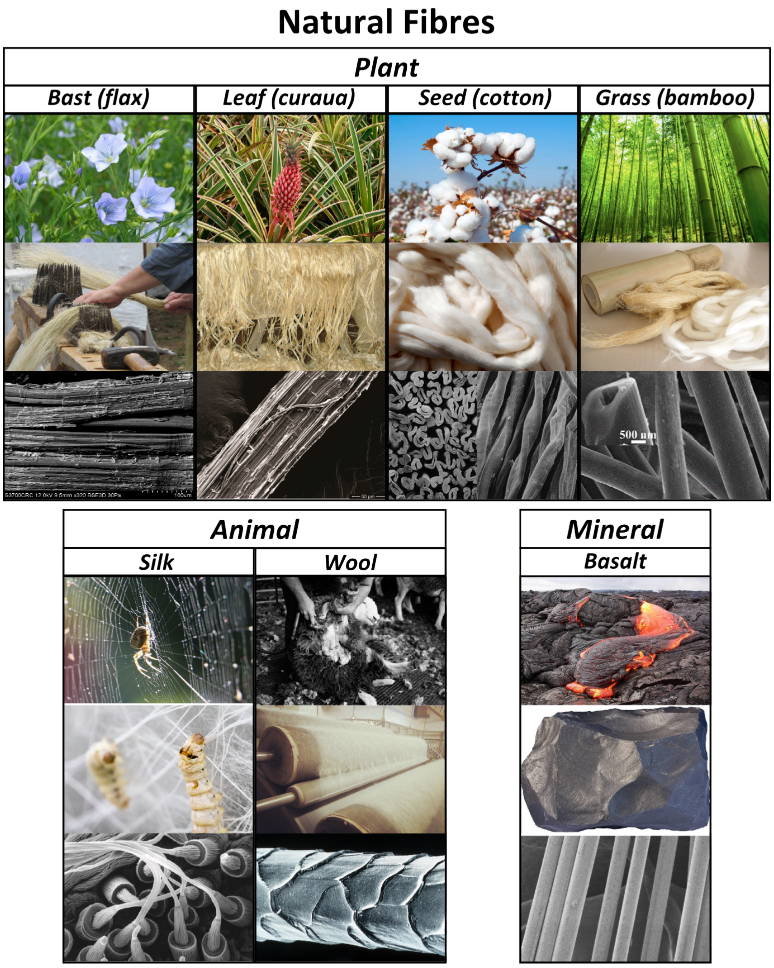

Figure 5. Classification of natural fibres through examples of sources, intermediate processes and end products. Source: [87].

3.2. Matrices

Bio-based resins have been developed based on precursor materials of 100% biomass origin or, more commonly, a hybrid blend of synthetic and biomass material to tailor for specific characteristic requirements [88]. The mechanical properties of bio-based and synthetic polymers are summarised in Table 3. Of the bio-polymers discussed, most have a bio content below 50%, implying they are majority synthetic polymers and arguably could be classified as synthetic polymers. However, for the purposes of this paper, polymers with a non-zero bio-content will be classed as bio-based. Within the broad field of matrices, the three key sub-divisions are thermosets, thermoplastics and vitrimers, each with their own set of disadvantages both technically and environmentally.

3.2.1. Thermosets

As a matrix, thermosets (such as epoxies, polyesters and vinyl esters) are often preferred in FRP composites due to their superior mechanical properties, durability and thermal stability. However, most engineering thermosets are not biodegradable nor fully recyclable, which indicates a higher EI. Complete reviews of thermosetting resin composites recycling processes have been presented by Pimenta et al. [89] and Oliveux et al. [90]: in general, the thermo-chemical processes required to reclaim the fibres for future use degrade the matrix, making its reuse challenging. Currently, the only way to fully reuse EoL thermosetting resin composites is to mechanically grind them and use them as a filler [91], but this is often not convenient due to the low return value. The majority of all synthetic epoxy in the composite market (around 90%) is based on the diglycidyl ether of bisphenol A (DGEBA) derived from epichlorohydrin and bisphenol A [92]. The synthesis, properties and applications of thermoset resins derived from bio-based sources, as alternative feedstocks to those derived from petroleum, have been discussed [93], with matrices obtained from furans, plant oils and starch, and advances in cellulose and nanocellulose indicated as future matrix feedstocks [94]. Numerous approaches for synthesising bio-based epoxies with functional groups derived from natural sources, such as tannins, cardanols, vegetable oils, woody biomass, lignin, terpenes, terpenoids and resin acids have demonstrated the ability of bio-based epoxy additives to enhance the toughness of polymer networks [95]. Bio-based thermosets derived from vegetable oil resources and terpenes have been studied to reduce the EI and their suitability for several applications have been demonstrated [96]. A bio-based epoxy resin, derived from vegetable oil and offering high fracture toughness, has been suggested to be the most appropriate in the current thermoset market [97]; other options include Ebecryl, pine and vegetable oil-based SuperSap epoxy, soy-based Envirez and linseed oil-based Vikoflex [98]. Cardolite has recently introduced cashew nutshell liquid technology to produce bio-based epoxy curing agents, diluents and modifiers which, according to LCA results, releases less carbon dioxide equivalent per kg of resin relative to petroleum-based epoxies during production principally through carbon sequestration [99]. However, thermoset resins remain challenging to recycle at EOL since they can not be melted and reformed.

3.2.2. Thermoplastics

Traditional synthetic thermoplastics, such as polypropylene (PP), polylactic acid (PLA), polyethylene (PE) and polystyrene (PS) are often touted as being recyclable at EOL [100] and they have been frequently paired with natural fibres to create NFRPs [101,102]. They can be easily manufactured into complex parts and, more importantly, provide good impact resistance. However they do require high processing temperatures, which can limit some applications for NFRPs, since natural plant fibres physically degrade over 200 °C, making then unrecyclable [103]. Polyglycolic acid (PGA) is a bio-based polyester with desirable mechanical properties, but owing to its high melting temperature (220 °C) it is incompatible with NFRPs [104]. Polyhydroxyalkanoates (PHAs) represent a promising class of bio-based polyesters: a long but somewhat chequered history follows their initial development to pilot plant-scale by ICI in the late 1980s and subsequent commercialisation as BioPol; however, interest faded at that time due to the relatively high cost. PHAs are naturally derived from microorganisms, and they exhibit a low density ($\sim$1.2 gcm^{-3} depending on crystallinity) and mechanical properties comparable to synthetic isotactic PP (with a highly regular distribution of methyl substituents on the polymer backbone) [105]. By adding hydroxy valerate to a PHA network, the resulting bio-based resin demonstrates a melting temperature and mechanical properties equivalent to PE [104]. It has been demonstrated that a more sustainable and competitive BC is achievable by using bio-based high density PE (HDPE) resin with natural fibres or components, such as wood flour, flax fibres and walnut shell flour [106]. Thermoplastic starch (TPS) is another biodegradable, renewable and low-cost bio-based resin, but has unsatisfactory mechanical properties and is subject to retrogradation [107]. A potential solution to this is to blend it with other bio-based or synthetic thermoplastics, increasing the renewable content and allowing for some biodegradation. Several TPS polymer blends are already commercially available [108] such as Bioplast®, Mater-Bi® and TPS/PCL, which have been successfully reinforced with various volume fractions of natural fibres, e.g., flax and ramie, obtaining tensile strengths in the range of 20 to 55 MPa [109]. Additionally, it was shown that blends of polysaccharides and starch appear to be compatible matrices with natural fibres [109]. LCA results have shown that, whilst synthetic polymers are the best economic alternative, polymers with higher content of TPS exhibit higher environmental performance [110]. The biodegradability and potential for thermoplastics to be reformed mean that they remain strong candidates for suitable NFRP pairing, but the low mechanical performance and creep drawback of bio-based thermoplastics are the main barriers to wider uptake [111].

Table 3. Properties of bio-based and synthetic resin systems, [1] Heat deflection temperature based on Envirez 70302 resin with 22% bio-based content, [2] Melting temperature of 100 wt.% bio-based HDPE Brasken SHA7260 min. 94% bio content, interpreted from the differential scanning calorimeter cooling cycle and second heating cycle, [3] Vicat A softening temperature for Biotec Bioplast.

	Stiffness (GPa)	Tensile Strength (MPa)	Density (kg m^{-3})	Maximum Service Temperature	Reference
Bio Resins					
Thermoset					
Bio-epoxy	3	69	1000	100	[112]
Unsaturated Polyester	2.5	73	-	90 [1]	[92]
Thermoplastic					
High Density Polyethylene	1.1–1.8	22–31.0	955	132 [2]	[113,114]
Thermoplastic Starch	2.4	34	1350	58 [3]	[108]
Polyglycolic acid	6–7	60–99.7	1500–1710	225–230	[115]
Poly(3-hydroxybutyrate)	3.5–4	40	1200	175–180	[116,117]
Synthetic Resins					
Thermoset					
Epoxy	2.41–4.5	27.6–130	1200	90–200	[114,118]
Polyester	2.06–4.41	41.4–90	1200	60–200	[114,118]
Vinylester	3.3–4.9	53–75	1150	>100	[118,119]
Thermoplastic					
Polypropylene	1.14–1.55	31–41.4	900	70–140	[114,118]
Polyphenylene sulfide	3–4	65–110	1300	130–250	[118,120]
Elium	2.6	5.6	1036	107	[121]

3.2.3. Vitrimers

Vitrimers are a relatively new class of polymer [122], and can be synthesised from thermoset, thermoplastic or elastomer precursors. Although they are technically crosslinked, the associations between the polymer chains are non-bonded interactions (i.e., not covalent in nature). This makes it possible for the polymer structure to switch by breaking and reforming the electrostatic associations and hydrogen bonds, under certain conditions, allowing the material to be reshaped and healed. The repairability, reformability and recyclability of vitrimers could make them more attractive than either thermosets or thermoplastics in some applications where high thermal or thermo-oxidative stability is not required [123]. The combination of Bentonite particles with a vitrimer matrix synthesised from epoxidised natural rubber has been investigated for composite applications, demonstrating their heat-driven, self-healing recyclability [124]. A vanillin-based epoxy vitrimer matrix was used to produce a high-performance carbon fibre composite, and partial matrix degradation was achieved under mildly acidic conditions, resulting in high yields of composite recyclate [125]. The use of vitrimers could also compensate for the disadvantages of natural fibres; for example, nanocomposites produced by the polydimethylsiloxane-based vitrimer exhibited high water resistance and strong overall adhesion, which is not typically awarded to NFRPs [126]. Other work in this field has produced a fully bio-based epoxy vitrimer from commercial epoxy soybean oil with fumaropimaric acid, exhibiting good shape memory, self-healing and reprocessing properties [127]. A fully bio-based polyimine vitrimer derived from fructose, was found to have a lower temperature requirement for synthesis and reuse than other vitrimers [128]. An imine-based hardener derived from a partially bio-based epoxy source was used to produce a vitrimer and paired with carbon fibre; closed-loop recycling of the composite was completed by removing the matrix in an amine solvent without degrading the carbon fibre or resin, which could then be used to produce recycled composites [129]. Furthermore, woven carbon fibre fabrics have been impregnated with powdered vitrimer matrices to fabricate composites rapidly; reshaping capability has also been demonstrated, suggesting the suitability of these materials for high volume production [130]. As fibre reinforced vitrimer composites are a very recent addition to the designer's tool kit, to date there has not been time to perform LCA and LCE: to establish the sustainability of this novel material class, LCA validation is urgently required.

3.3. Interface

As a rule of thumb, unless a natural fibre has undergone additional processing, it has a rougher surface compared to a synthetic fibre. In principle, this can aid mechanical interlocking with the matrix, but the presence of hydrophilic hydroxyl groups may form hydrogen bonds with adventitious moisture, competing with those formed with a polar matrix resulting in poor mechanical performance as a composite [82]. Additionally, the reactive functional groups of the natural fibre may be covered by pectin and waxy substances that behave as a barrier, preventing effective fibre-matrix bonding [123]. To overcome this issue, chemical treatments are applied to the fibre to provide increased wettability, water resistance, IFSS and compatibility with the matrix. Several chemical methods exist, such as alkaline treatment, silane treatment, acetylation, benzoylation, peroxidation, sodium chlorite, isocyanate and fungal treatments [103]. The most common of these is the addition of sodium hydroxide, a highly alkaline species, which removes a portion of lignin, wax, pectin and oil from the system through a saponification mechanism, altering the crystallinity of the system. This increases the fibre-matrix bonding strength and the overall NFRP mechanic performance. However, these treatments can be expensive, and release post-treatment chemicals and any by-products as waste. Furthermore if the treatment yield is too low, then it can even limit the interfacial improvements [131]. Alternatively, fungal treatments have been demonstrated to be as effective as alkali treatments in terms of improving mechanical properties, yet are also potentially lower in EI, as they are based on the enhancement of a natural treatment process [132]. To provide NFRPs with further properties, such as flame retardancy or water resistance, treatments will always be required and the EI of such treatments should be considered with LCA during the design phase.

4. Production

Natural plant fibres and bio-based materials for BCs are cultivated on agricultural land and thus photosynthesise during production. This absorbs carbon dioxide from the atmosphere and locks it in the plant's molecular structure, storing the carbon and releasing oxygen as an output, i.e., carbon sequestration [133]. This is all powered by solar energy, an abundant and renewable energy source, and results in a reversal of GHG emissions, reducing harmful global warming. In stark contrast, the extraction of raw materials to produce glass or carbon fibres and synthetic polymers emits large amounts of carbon dioxide into the atmosphere; a significant contributor to climate change. It is by virtue of the lower carbon emissions and lower scores from other EI categories that bio-based materials have received such significant attention in recent years.

Unreliable harvest yields, due to external factors, such as the microclimate, temperature and humidity, represent a significant challenge for BCs. Unsustainable farming practices are adopted to minimise heterogeneity during cultivation, e.g., the use of agrochemicals, the production and application of which can grossly alter the energy consumption of plant growth. Other impacts can include land use change, water consumption, biodiversity loss, significantly reduced soil quality and increased stratospheric ozone depletion due to nitrogen dioxide emissions from fertiliser application [15,134,135].

Deng compared the EI of producing a GFRP (glass/epoxy) electrical circuit board component and an equivalent made from NFRP (flax/linseed oil) [15]. The use of the NFRP over GFRP significantly lowered the EI from GHG emissions associated with GF production, but there was an increase in the marine ecotoxicity and eutrophication from surface fertiliser run off, applied to the land for natural fibre growth. While the energy required for cultivating flax in the UK was low, the agrochemicals and retting processes increased energy consumption significantly [136]. Essentially, the environmental footprint of natural fibre or biomass production will come from: tillage, sowing, harvesting and fertilising processes, which depend on the particular fertilisers or agrochemicals used [135]. The cultivation process is a key area of BC material production, which is limiting their environmental performance.

5. Processing

Once the cultivated natural plant fibres have grown, they need to be harvested and transformed into continuous fibres. Seasonal fluctuations of external factors affect the height of the plant and therefore strength and density of the fibres. For certain performance applications where designs must meet a given strength, additional processing stages may be required to ensure mechanical characteristics of the final composite are acceptable [137]. Fibre substructure processes, such as mat production, fibre yarns, granule production, fibre preparation and fibre treatment could represent a large proportion of the processing emissions [135].

In Europe, flax and hemp yarns are the most commonly used reinforcements for BCs. After harvest, they are both processed through different methods, depending on their desired resulting properties. Extra treatments that give BCs the characteristics required of specific applications, e.g., flame retardants, are incorporated at this stage. Since bio-based materials are hydrophilic in nature, they can be treated to prevent moisture absorption during their service life. Any treatments at this stage will increase the EI and economic cost, due to the production and application of these chemicals. However, LCAs demonstrate that no method is more efficient overall, and that any use of chemicals significantly negatively affected the EI score. It was also noted that, in particular, the lack of technological development in processing methods is seen as the decisively limiting factor for the natural fibre industry in Europe. The large labour input at the processing stage has limited hemp reinforcement production to Hungary and Romania where labour costs are low, and this blocks the wider spread of fibre production to Western Europe [138].

Crucially, the processing temperature for natural fibres is absolutely limited to 200 °C, which restricts the composite manufacturing options available and reduces the possible applications of NFRP [135]. The key limiting factor in selecting a processing temperature is the influence that this has on resin viscosity. If a resin can only achieve permeation of a natural fibre fabric at a temperature greater than 200 °C, then its mechanical properties will be sub-optimal [139]. As such, either a greater mass of material would be required to achieve equivalent properties or the material would not be selected.

While the bio-based resins on the market are relatively new materials (approx. 10 years), fossil-based resins are more mature (50–60 years) and, therefore, are an optimised product in a heavily streamlined and competitive supply chain with access to stable markets and policy structure. Bio-based resins are, by contrast, produced in limited numbers of smaller-scale facilities, with emerging but fractious supply chains, and this affects the stability of pricing and access to assured markets [140].

By way of example, starch is relatively inexpensive in the UK as a bio-based resin feedstock, but prices can very considerably: starch from wheat is GBP 263/tonne but starch from cassava can cost GBP 986/tonne [141]. Cassava, being the superior starch feedstock is also grown in other countries around the world: in Ghana the cost is USD 1192/tonne, but in Thailand it is USD 275/tonne. There is also significant variability in the quality of the starch feedstock, especially from developing countries where quality inspection rules are not so stringent, and due to long times spent in transit. When selecting these resin feedstocks, transport costs (economic and environmental) must be considered and incorporated into the LCE model at the design stage too. Whilst, in theory, these abundant and renewable bio-based feedstocks should be more economically and environmentally efficient than extraction and refining of synthetic fossil-based feedstock, this is often not yet the case.

Similar issues regarding quality variability and supply chain are present for some natural fibre reinforcements grown globally too. Whilst natural fibre alternatives to synthetic reinforcements are showing traction, more research on fibre processing, interfacial bonding, and moisture sensitivity control is required in order to compete with glass fibre [19]. A promising first step has been the recommendation, within a number of papers, to use natural fibres in conjunction with synthetic fibres in a hybrid structure [66].

6. Use

The additional upstream environmental burden of producing FRPs over traditional materials, such as steel and aluminium, has been justified downstream during the use phase by offering longer service lives with lower maintenance impacts, contributing to the sustainable solution that composites can offer. Currently, information regarding the maintenance, durability and service efficiency parameters of BCs is incomplete, and these are critical to ensure that BC components will have the same use life length as their synthetic FRP counterparts [16]. The intended application of the composite will have significant influence over the EI and the economic cost. Whilst BCs have the advantageous light-weighting properties for transportation applications, issues regarding their durability mean they are unsuitable for applications under the hood of vehicles and are limited to decorative or cosmetic interior applications; the same is true for aircraft applications [142].

On a more positive note, the automotive industry has already established a strong demand for NFRP during the last decade: even in 2012 over 95% of NFRPs commercially produced in the EU were used for non-structural automotive components, manufactured predominantly by compression moulding [143]. Natural fibres, such as ramie, flax and jute have significantly superior sound dampening capabilities over their synthetic competitors that are attractive for automotive interior applications, such as door panels, dashboards, roof liners and seat shells [144,145]. Additionally, components made from hemp composites do not splinter or leave sharp edges when cut, an important feature for the automotive sector when considering collisions [146].

There are several niche areas where the multifunctionality of NFRPs have the potential to be explored. The conductivity (i.e., dielectric performance) of natural fibre composites was discussed in a review by Al-Oqla et al. [147]. The dielectric constant is the measure of a material's ability to store energy from an incident electric field, and a high dielectric constant implies the material can absorb electromagnetic radiation. A composite of this kind could be classed as multi-functional, absorbing radiation whilst supporting a system structurally, although it should be noted that the absorption of moisture would raise the dielectric constant. In this context, sisal/polyester and jute/polypropylene have undergone testing and indicated promising performance [148,149]. Feng et al. demonstrated that a bio-based benzoxazine resin had encouraging dielectric properties and an area for future work could be its coupling with a natural fibre to produce dielectric BCs [150]. Cured polybenzoxazines are traditionally quite brittle in engineering applications and the composites would require significant toughening before use. Yang et al. studied cotton, wool and flax fibre yarns applied to an artificial muscle actuator to produce high-performance sportswear [151]. The yarns were twisted into artificial muscles by a motor as a smart fabric concept. To mimic perspiration stress from physical activity on the fabric, moisture was added, causing the yarns to contract and a flap to open, releasing heat and cooling the user. Additionally, flax and hemp fibres have high damping and absorption capacity relative to synthetic fibres, resulting in their use in automotive, sporting goods and musical instruments [152,153]. Bio-based resins have also found novel application as hygienic interior decorative coatings: a bio-based acrylic chitosan-nano silica hybrid resin, with anti-bacterial properties and hydrophobicity, minimises the risk to human health by reducing exposure to harmful synthetic resin irritants [154].

The inherent flammability of BCs means they are wholly inadequate for application in high-rise constructions, which have stringent fire safety regulations [155]. Additionally, since bio-based materials are naturally hydrophilic, if left untreated over their service life they will be prone to fungal and bacterial growth, resulting in higher maintenance impact and costs. However when BF/epoxy composites were exposed to seawater ageing at different temperatures, their mechanical performance was found to be similar to that of GFRP with the same epoxy matrix after sea water saturation, which suggests the potential use for BF composites in marine structures [156].

As more companies face pressure and international target commitments to reduce their carbon dioxide emissions, other industries are turning towards natural or bio-based products. The fashion industry, in particular, has seen a marked increase in demand for fibres like flax and hemp, generating more competition for the dwindling amounts of land available, which may result in a price hike. The automotive industry is heavily price-dependent and may not be able to compete with these industries for bio-based materials [137]. This has also stimulated comment within the BC sector that their limited uptake to date has been contributed to by a lack of "political will", including policy instruments, tax relief or stimulation packages that may incentivise investment, and this could be due to the deeply rooted global market dominance of fossil material companies [157]. However, this setback is driving innovation within the BC field and, as they become more mainstream, it is hoped they will experience wider acceptance by the markets. For example, fibre precursor and resin feedstocks are now being developed from algal blooms, reducing the dependence on scarce land resources for material production, as well as addressing the eutrophication that has caused the exponential growth in toxic blooms all over the world [158–162].

7. End of Life (EOL)

Owing to the environmentally damaging nature of material extraction and production, the overarching aim of the circular economy model is to keep resources within the industrial system loop in a sustainable way, to prevent the unnecessary production of virgin materials [163]. As a result, composite waste landfilling has recently been prohibited in an increasing number of European countries—for example, Germany [164,165] and EU law now requires 95% by weight of all automotive vehicles produced in the EU to be reused, recovered or recycled at the end of their life [166]. Unfortunately for BCs, any form of reclamation technology is not currently possible due to operating temperatures of more than 200 °C, e.g., pyrolysis requires temperatures between 450–700 °C, which would completely burn bio-based materials [167]. Chemical processes, such as solvolysis, would also damage bio-based materials beyond repair. Vitrimer resin technology may offer low temperature or low energy repair–reuse–recycle options based on the Waste Hierarchy preference, but this has not yet been qualified by an LCA.

Biodegradability refers to the ability of organic material to break-down with the help of microorganisms, such as bacteria and fungi, within a certain time frame. These microorganisms change the materials' molecular structure to give base substances such as water, carbon dioxide, methane, basic elements and biomass [168]. If biodegradable fibres were combined with a biodegradable resin this would produce a biodegradable composite. Under the correct conditions, biodegradable materials can be degraded relatively quickly by microbes and natural processes, returning nutrients back to the biological system to prepare for the next material cycle. When managed correctly, the environmental benefits are numerous: improvements in soil quality, increased biodiversity, a reduction in waste going to landfill and in overall global warming potential. Fully biodegradable composites, although extremely rare for structural applications, are not recyclable in the traditional sense of keeping materials within the technical system. Figure 6 shows the biodegradability of the main fibres and resins discussed within this paper in their purest form, i.e., of 100% synthetic or 100% bio-based origin. It is anticipated that some bio-resin blends that include some non-biodegradable constituents could exhibit a certain amount of biodegradability, depending on the respective amounts; however, this has been understudied, as of yet.

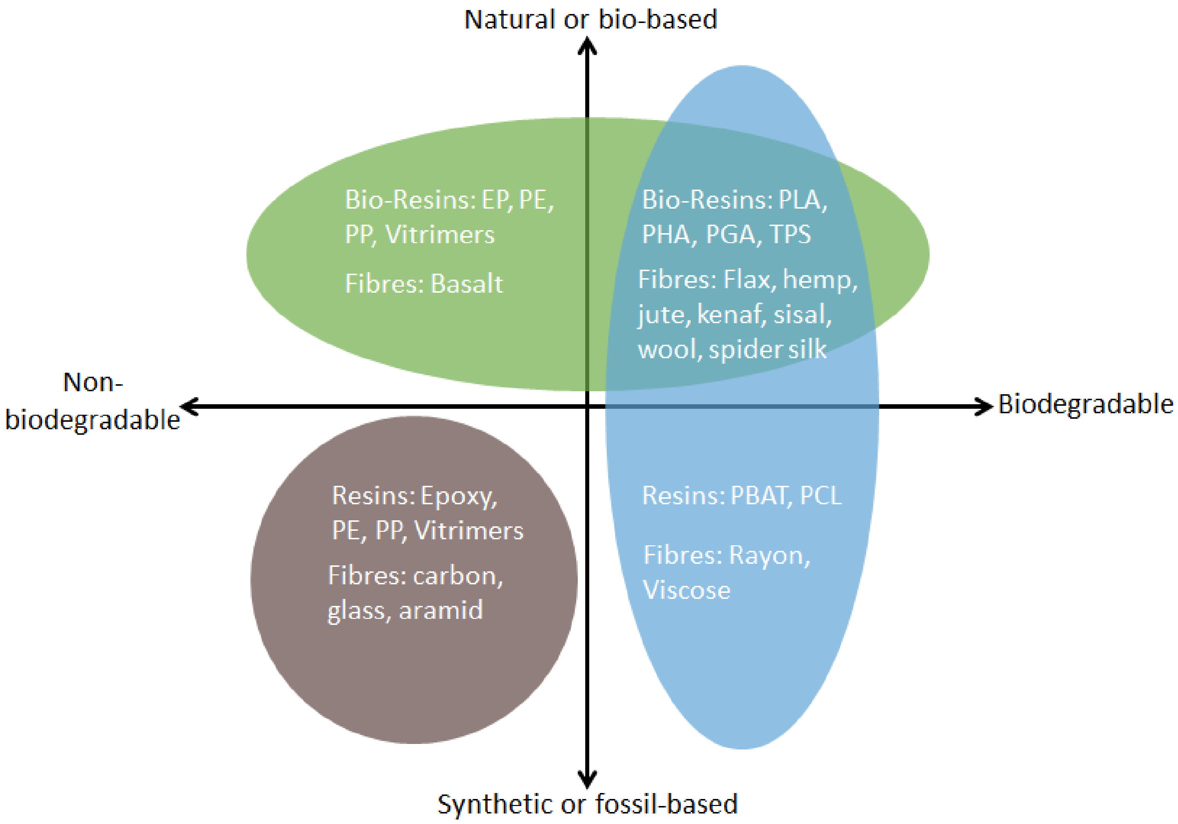

Figure 6. Biodegradability of the most common bio-based and synthetic composite fibre reinforcements and resin matrix systems. The data are taken from references in Section 3 and [140,169,170].

The risk of contamination from synthetic composite wastes has subsequently meant that industrial composting facilities for biodegradable BCs are underdeveloped [171]. Conversely, if synthetic composite constituents are contaminated with bio-based materials (for example, blended bio-resins), the longer-term durability of reusing composite structures cannot be guaranteed. Some studies have examined the mechanical recycling of BCs as a recycling route, possible through grinding down the composite to the desirable size for filler material [171,172]. Whilst the EI of the recycling process must remain extremely low in order to be environmentally and economically feasible, this could become an attractive option for the automotive sector which have a legal obligation to recycle/reuse 95% of

EOL vehicles. Unfortunately, this may compromise the onward application of the recyclate due to the decrease in resulting properties, such as tensile stress, impact strength and E-modulus of fibres, as well as decrease in the molar mass of the resin.

The only other option available for the EOL of BCs within the traditional Waste Hierarchy framework is incineration, with the possibility of heat recovery (Figure 4), which will release the sequestered carbon back into the atmosphere as carbon dioxide, along with the release of other potentially harmful off-gases. The combustion of bio-based materials, such as sisal or kenaf fibre, has a significantly lower gross calorific value than for glass or carbon fibres, and would result in a comparatively lower EI than the incineration of purely synthetic FRP composites [163].

One of the leading challenges for waste BCs is that the disposal options available are not considered during the early product design stage. The focus has traditionally been on the performance and durability. Whilst the hybridisation of natural fibres with synthetic and blends of bio-resins do appear to offer environmental benefits at the production and use stages, they can cause more complications at the EOL stage. This furthermore highlights the importance of adopting an LCE approach at the design stage of a composite product.

8. Conclusions

BCs can form part of the circular solution for the Sustainable Recovery plan, allowing carbon sequestration at production and return to raw at end of life, and enabling the manufacture of high-value products. However, composites with materials of mixed origin (bio-based and synthetic) present technical and environmental challenges different to those of purely synthetic composites during the life cycle.

LCE offers the opportunity to consider each stage of a composite's life cycle before the product design is finalised and moves to production. Effectively using the LCE framework will encourage more innovative design from the outset, incorporating the best of the multifunctional features of BCs and synthetic FRPs. By recognising that materials of different origin behave in different ways over the entire life cycle, they can be accordingly treated as such. The completion of LCE analyses could, for example, result in the identification of other markets or applications for BCs that are better suited to their natural intrinsic properties instead of the resulting properties after multiple layers of processing so they mimic the behaviour of synthetic composites. An alternative solution could be to organise BC and synthetic composite components to great effect for the same product, targeting more replaceable components for BCs and the more durable ones for synthetics. Even though there is a wealth of data within the literature to quantify the coupon-level behaviour of BCs, more examples and data are needed at laminate and structural level to address the gaps in design of primary structures. BCs are not as well-documented in LCE assessments compared with the synthetic FRP composite and metal systems, and by increasing the amount and quality of LCE reports available, challenges associated with their use will be highlighted and addressed. This also provides the potential to uncover advantageous novel behaviour and multifunctionality harnessed through their non-linear nature, such as shape memory composites.

For natural fibres, in particular from the bast group comparable with glass fibre, the use of pesticides and unsustainable farming methods cause the largest EI during their production. They are also competing with other industries, such as fashion, biofuels and agriculture, for a dwindling amount of land, the supply and demand of which can lead to significant price instability. Extra treatments of natural fibres after harvest are a way to improve IFSS with matrices and the overall mechanical performance of BC during use. However, there is no consensus about the efficiency of treatments, and they increase the EI of the processing phase of their life cycle. Furthermore, popular synthetic composite manufacturing methods are not suitable for BCs, which would degrade at processing temperatures over 200 °C degrees.

Progress has been observed regarding matrices made from bio-based materials: renewable thermosets, recyclable thermoplastics, biodegradable blends and the innovation of a new polymer class, vitrimers. These can be considered as strong candidates to address EOL issues associated with FRPs in lower temperature applications, since they have a wide range of greener solutions (such as reuse–repair–recycle), as well as being derived from renewable bio-based materials.

At the end of its use, a BC has the potential to return to earth to biodegrade and replenish the soil for new material growth. However due to their processing and resin pairing, biodegradability could be compromised. Legal frameworks also block the landfilling of composites within Europe now, and the recycling options for BCs remain limited due to the high temperatures required. Currently the only option available is incineration with heat recovery. More research is urgently needed on the EOL handling data for BCs, which can be used to implement legal and fiscal mechanisms to encourage the adoption of greener solution for sustainable recovery, e.g., industrial composting facilities.

BCs have been available on the composite market for some time now, yet their widespread uptake has been limited, and the academic literature still focuses on their potential, instead of actual, applications. Despite the environmental advantages over their synthetic counterparts, there are issues over compatibility with traditional applications, such as their hydrophilic nature, low thermal resistance, flammability and variation across fibres. The geographical locations of certain bio-based feedstocks means establishing pathways to manufacture or market can also be a challenge when compared to the streamlined synthetic material route. Competition from other industries, such as agriculture, fashion or even land for human settlement remains a growing issue, and as a result is driving innovation in other bio-based feedstocks; for example, fibres from algal blooms.

This could be an exciting time for BCs as they have the potential to facilitate the migration towards post-pandemic sustainable recovery, yet only when lead by effective LCE incorporation that can realise the right application for the right composite.

9. Further Work

In order to realise the full potential of BCs as part of the Sustainable Recovery plan, further work is required in the following areas: Basalt fibre and vitrimer resins are promising materials that need to be inspected under the LCA lens to facilitate their adoption by industry. The length of the functional use life of BC materials need to be better understood and quantified, before effective LCA decisions can be made. This work would also assist with the available EOL options, in particular, DfRu/DfRp. Industrial composting facilities need to be explored for biodegradable composites in order to maintain the flow of nutrients through the biological cycle. A deeper understanding about the complexities of EOL BCs made of mixed material origin (NFRPs, NFBPs and BCs that contain some non-biodegradable material elements) and the development of effective recycling treatment options according to the Waste Hierarchy framework. This would aim to keep synthetic materials within the technological system, and if degraded, downcycle or return the bio-based material elements to the biological system. With this strategy for future work in place, a wider uptake of design tool kits such as the LCE approach and DfX for BC and traditional composite products achieving greater harmonisation can be accomplished.

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