Biocomposites

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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.

Biocomposites | Sustainable Recovery | Life Cycle Engineering

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.

A clear distinction is made between composites of synthetic or bio-based materials:

- 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.
- 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.

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 [11].

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 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 for sustainable recovery [12]. 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 reduces EI for that component [13][14][15][16][17][18][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, e.g. processing constraints, limited durability, poor environmental and fire resistance (Figure 1). 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. Conventional design factors, such as technical performance and cost, are combined with a product's EI from LCA through a process commonly known as life cycle design, i.e. the Life Cycle Engineering (LCE) framework.

2. Biocomposites as a Solution for a Sustainable Recovery

BCs can form part of the circular solution for the Sustainable Recovery plan by enabling the manufacture of high-value products with the potential for carbon sequestration at production and biodegradation at EOL. 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 [20]. 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 to mimic the behaviour of synthetic composites [21][22]. 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 [23]. 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 [24].

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 the interfacial shear strength 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 [25]. Furthermore, popular synthetic composite manufacturing methods are not suitable for BCs, which would degrade at processing temperatures of over 200°C degrees [26].

Progress has been observed regarding matrices made from bio-based materials: renewable thermosets [27][28], recyclable thermoplastics [29], biodegradable blends [30][31] and the innovation of a new polymer class, vitrimers [32]. 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 a post-pandemic sustainable recovery, yet only when lead by effective LCE framework incorporation that can realise the right application for the right composite.

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