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A perspective on biodegradable polymer biocomposites - from processing to degradation

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Abstract

Given the greater global awareness of environmental impacts of plastics and the need to develop alternative materials from renewable natural resources, there has been an increasing drive over recent years to develop biobased and biodegradable composites, especially those produced from agro-industrial waste and byproducts. This perspective provides a brief introduction to the field as well as discussing some of the critical aspects to be considered as we accelerate the development of these novel alternative materials for a range of applications.

Keywords Biodegradable polymers, Natural fibres, Fibre reinforced composites, Processing, Biodegradation

Introduction

Fibre reinforced plastic composites have found applications in a wide range of high- and low-end products, from automotive to aerospace, ballistic, construction industry, interior furnishing and biomedical science applications through to food packaging, pallets and commodity tableware [1, 2]. The addition of fibres allows the final composite product to overcome some of the limitations of current plastics for these applications, such as low modulus and poor thermal stability [2, 3].

However, while the initial suite of commercialised composite materials was comprised of inorganic fillers such as glass fibres and ceramics blended with non-degradable polymer matrices such as polyethylene (PE) and polypropylene (PP), a demand for more sustainable products is driving the development of bioderived and biodegradable products [2, 3]. Thus, composites based on organic fillers, such as lignocellulosic-based fibres, coupled with biodegradable polymer matrices (whether bioderived or synthetically derived from petroleum), have been emerging rapidly into the market [4]. These materials offer attractive advantages over traditional composites, such as being biodegradable and/or recyclable as well as in many cases being fully bioderived, as well as non-toxic, with high tensile and flexural modulus, typically processible at a lower temperature, with better electrostatic properties, vibration damping (absorption), thermal insulation, and sound (absorption) attenuation, as well as being electrochemically non-corrosive and having tuneable properties for specific applications [5]. The fibres themselves are typically low cost and relatively light weight with high specific strength and in abundant supply [5]. Their size can also cover a huge range, from macroscopic wood pieces through to cellulose nanoparticles.

There are also some limitations to the use of biodegradable plastics in composite applications, such as the higher cost of the matrix, poor moisture and/or gas barrier properties, slow crystallisation rate, poor thermal stability and narrow processing windows [6].

Overall, specific challenges that have to be overcome for the commercialisation of biobased and biodegradable composites based on natural fibres include [3, 6]:

- The incompatibility between hydrophilic lignocellulosic fibres and hydrophobic polymer

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that leads to an overall reduction in mechanical properties and stability.

- The requirement for mechanical and physical stability under a service environment (particularly with respect to moisture uptake).
- A lack of understanding of the rate and extent of biodegradability that constitutes the end-of-life environmental impact, particularly in different environments.

To address these issues, it is important to understand the basic properties of the core components of polymer biocomposites and the processing and other strategies that have been adopted to maximise their material performance. The influence of fibrous fillers on the lifetime stability in use and ultimate biodegradation of polymer matrices also needs to be understood.

Classification and properties of natural fibres

As shown in Fig. 1, there are three types of natural fibres: plant-derived, animal-derived and minerals [7]. Natural mineral fibres, such as asbestos fibres and those that are formed from vitreous processing of minerals such as basalt fibres, are non-metallic and inorganic in nature and typically deliver excellent material performance in polymer composites [8]. However, many are problematic in application, having major health impacts (such as being carcinogenic) when inhaled [9], as well as being non-degradable and of a fine, fibrous form. This perspective therefore focuses on natural organic fibres.

Animal fibres such as wool and silk are primarily composed of proteins such as keratin, fibroin, collagen and chitosan [10]. Compared to plant fibres, animal fibres tend to be more flexible, have a higher surface toughness, high aspect ratio, and to be less hydrophilic [10].

By contrast, plant fibres are lignocellulosic in nature, comprised of lignin, cellulose, hemicellulose, pectins and waxes, and hence more hydrophilic [11]. They can be classified as primary or secondary, where primary plant fibres are those that are grown specifically for use as fibres (cotton, hemp, sisal for example) while secondary fibres are those that are a byproduct of production (e.g. bagasse) [11]. Fibres can be extracted from every part

Fig. 1 Classification of natural fibres [4, 6–8, 12]

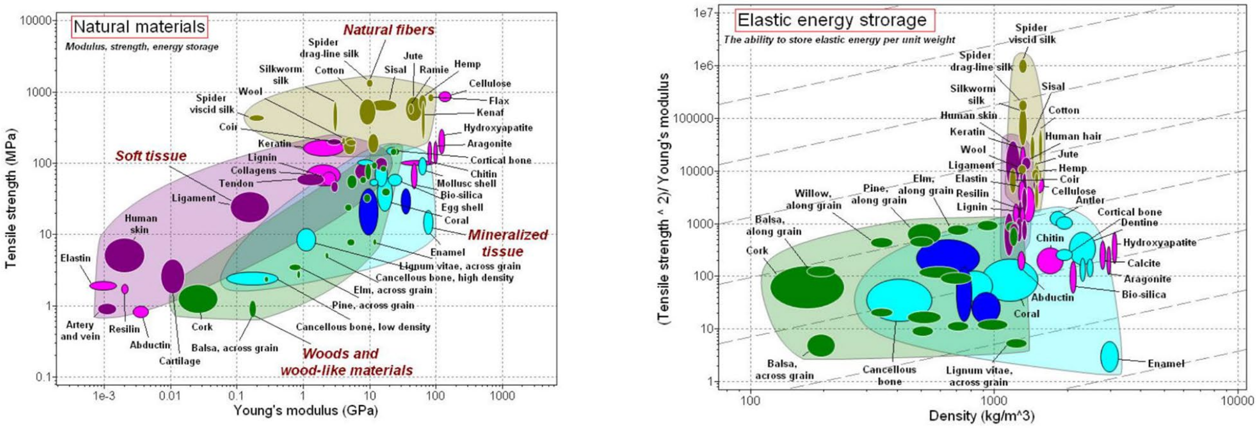

Fig. 2 Ashby plots showing material properties of natural fibres relative to other natural materials, with (left) Young's modulus and tensile strength and (right) capacity to store elastic energy per unit weight. (Reprinted with permission from [13], Copyright © 2007 Professor Michael Ashby and Granta Designs)

Table 1 Typical mechanical properties for fibres [1, 4–6, 8, 11, 12, 15–26]

Fibre	Tensile Strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Density (g/cm^3)
Ramie	220–938	27–128	1.2–3.8	1.5–1.56
Cotton	287–800	5.5–12.6	6–8	1.5–1.6
Sugarcane Bagasse	179–290	17–27	1–4	1.2–1.25
Flax	345–1500	27–85	1.2–3.2	1.4–1.5
Bamboo	140–600	11–32	1.4–3.2	0.6–1.1
Jute	393–800	10–30	1.2–1.8	1.3–1.5
Sisal	400–855	9–38	2–7	1.3–1.5
Hemp	310–900	30–70	1.6-4	1.4–1.5
Banana	162–914	27–34	2-5.3	1.3–1.5
Coir	135–240	4–6	15–40	1.1–1.25
Kenaf	223–1191	14–53	1.6–4.3	1.22–1.4
Wood	45–121	7-13.5	1.6	1.2–1.4
Wood pulp	5-195	1–18	2–4	1.5
Wool	50–315	2.3-5	13.2–35	1.3
Silk	100–1500	5–38	15–35	1.3–1.4
Glass	2200–3600	65–86	4-5.5	2.6
Carbon	3400–4000	130–345	0.5–1.2	1.4–1.8

of a plant, from roots to leaves and fruit. Bast fibres, for example, are those that come from the stem of a plant and tend to have excellent Young's modulus and flexural strength, while leaf fibres have greater impact properties [10].

The Ashby plots in Fig. 2 illustrate some material properties of some of these natural fibres, with silk and cellulose fibres being the strongest, and with silk in particular showing an extraordinary capacity to store elastic energy [13]. Bast fibres (flax, hemp, jute, and ramie), also, are as strong as steel wire and stiffer than E-glass fibres based on equivalent weights [14].

A summary of the typical mechanical properties for a range of plant fibres is given in Table 1, noting that there is, in general, a very wide range of values reported in the literature for these materials, pointing again to their inherent natural variability based on many factors such as where they are grown, under what conditions, as well as cultivar used, the age of the plant, and extraction process adopted [6]. It should also be noted that the fibre properties are known to be dependent on the amount of cellulose present, the microfibrillar angles, and the degree of polymerisation of the cellulose in the fibres, with structure/morphology being strongly associated with lignin content [5].

The extraction of fibres from natural animal or plant materials is a critical process that governs the final properties of the isolated product. In the case of animal fibres, the process is often quite mild, consisting of simple harvesting then washing, typically with mild surfactants. By contrast, plant fibre separation and extraction (or retting) is typically a much more complex and energy intensive process since deconstruction of a complex matrix is required, with approaches ranging from biological to mechanical, physical, chemical, protein and enzyme-based retting. A summary is provided in Table 2 of the commonly accepted strengths and weaknesses of biofibres when used in polymer biocomposites.

Nanofibres such as nanocellulose are a separate subclass of reinforcement agents, comprising cellulose nanocrystals (which have a whisker shape or a short-rod-like shape with a length in the range of 100–500 nm and a diameter of 2–20 nm) and cellulose nanofibres (with a diameter of about 1 to 100 nm and a length of about 500 to 2000 nm) [28]. Nanocellulose materials have gained growing interest owing to their attractive and excellent characteristics such as abundance, high aspect ratio, better mechanical properties, renewability, and

Table 2 The merits and demerits of plant fibres for use in polymer biocomposites, reprinted with permission from [27]. Copyright © 2023 Elsevier

Positive aspects	Concerns
Highly abundant	Lower strength compared to synthetic fibres in some cases
Low specific weight	Higher moisture absorption (hydrophilic)
Low cost	Wettability
Renewable resource	Swelling
Biodegradable	Poor fire resistance
Recyclable	Concerns over durability
Lower environmental impact during production? (to be assessed)	Can be odours during degradation
No or minimal residues when incinerated	Low thermal resistance (~ 200 °C)
No skin irritations	Restricted maximum processing temperature (~ 200 °C) -also limits polymer matrix choice
Corrosion resistance	Poor microbial resistance
Acoustic and thermal insulation	Tendency to agglomerate (hydrogen bonding between fibres)
Low wear	Non-standard processing and post-processing
Easy and safe handling	Inherent variability (season, site, variety etc.) – including of quality
Non-toxic	Supply chain issues
CO_2 cycling	

biocompatibility [29]. The abundant hydroxyl functional groups allow a wide range of functionalisation via chemical reactions, leading to developing various materials with tuneable features [29]. The production of these materials typically involves chemically and energetically intensive pretreatments, such as through the use of 2,2,6,6-tetramethylpiperidine N-oxyl (TEMPO) chemical processes or, for more readily isolated fibres, the use of strong caustic solutions, followed by more or less aggressive refinement/milling/micronizing) [28]. More recent approaches involve a range of technologies designed to be more direct and leading to more intact fibres with good aspect ratios and high crystallinity (Figs. 3, [30]).

Classification and properties of biodegradable polymer matrices

Biodegradable polymers are those that can be degraded by the actions of naturally occurring organisms such as bacteria, fungi, and algae, through cell mediated phenomena, ultimately breaking down into CO_2, water and biomass in the presence of oxygen, or to CH_4, water and biomass under anaerobic conditions [31, 32].

These biodegradable polymers can be classified as bioderived or fossil-fuel derived, and the environments under which these polymers will biodegrade varies depending on the polymer type, with poly(lactic acid) (PLA) requiring industrial composting conditions above 58 °C to biodegrade, remaining relatively undegraded for extended periods (years) under ambient conditions in soil or water [31, 32]. This is due to the fact that there are limited organisms in the natural environment that can degrade PLA, and hence the process of degradation is predominantly driven by abiotic (bulk) hydrolysis, and is

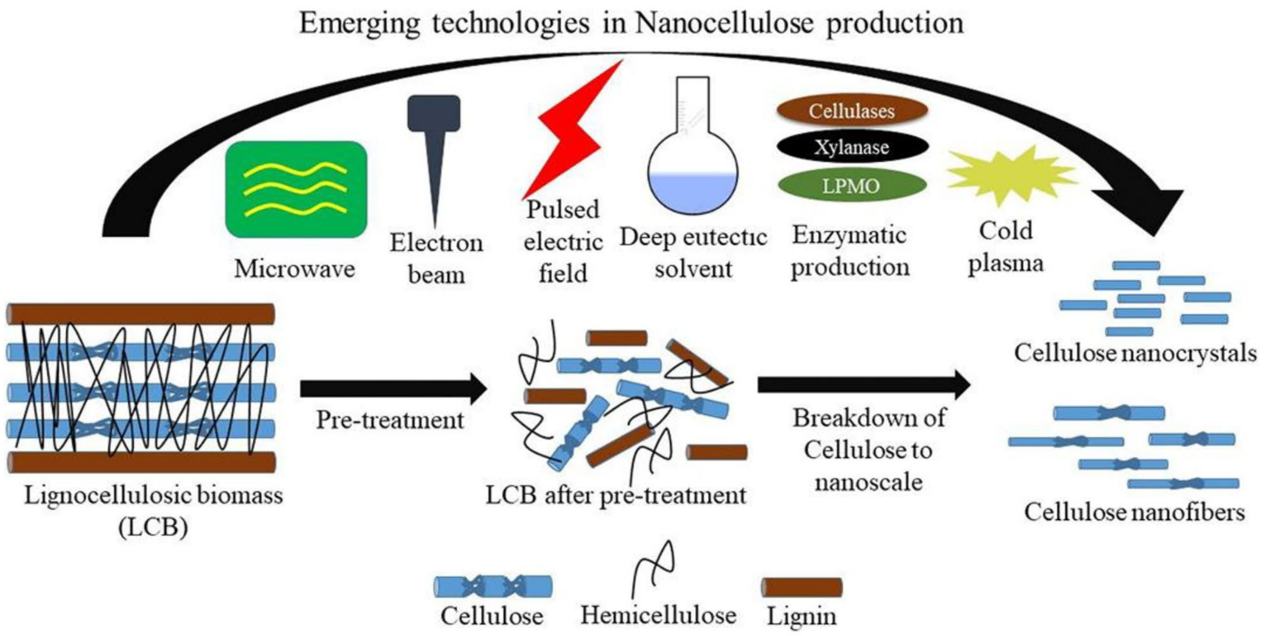

Fig. 3 Emerging technologies in nanocellulose production, where LPMO is lytic polysaccharide monooxygenases [30]. (Reproduced under Creative Commons CC-BY)

faster above the glass transition os around 58 °C [31, 32]. By contrast, other polymers such as polyhydroxyalkanoates (PHAs), especially poly-3-hydroxybutyrate (PHB) and poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV), and polycaprolactone (PCL) are far more readily degraded under ambient conditions due to the widespread presence of organisms that can produce enzymes capable of accelerating the hydrolysis of the ester groups in these molecules (Fig. 4) [31, 32].

For applications where biodegradability and/or the potential to be recycled is a core requirement, the polymer matrix also needs to be thermoplastic, since thermosets are resistant to degradation and biodegradation, being tightly crosslinked network structures [33].

Within a biodegradable composite matrix with natural fibres, the polymer matrix serves many functions [33, 34]:

(i) to adequately wet out/coat the fibre during processing, and (in related functions) to be chemically and thermally compatible with the fibres;
(ii) to enable good transfer of stresses to the fibres through good surface adhesion and/or friction;
(iii) to protect the fibres from surface damage during use;
(iv) to disperse the fibres, limiting agglomeration and preventing crack propagation;
(v) to have sufficient shear and tensile strength in its own right to deliver mechanical integrity to the biocomposite product under load and strain; and
(vi) to have appropriate fire resistance.

The typical mechanical properties of some of the more commonly used biodegradable polymers are summarised in Table 3, showing that in comparison with fibre

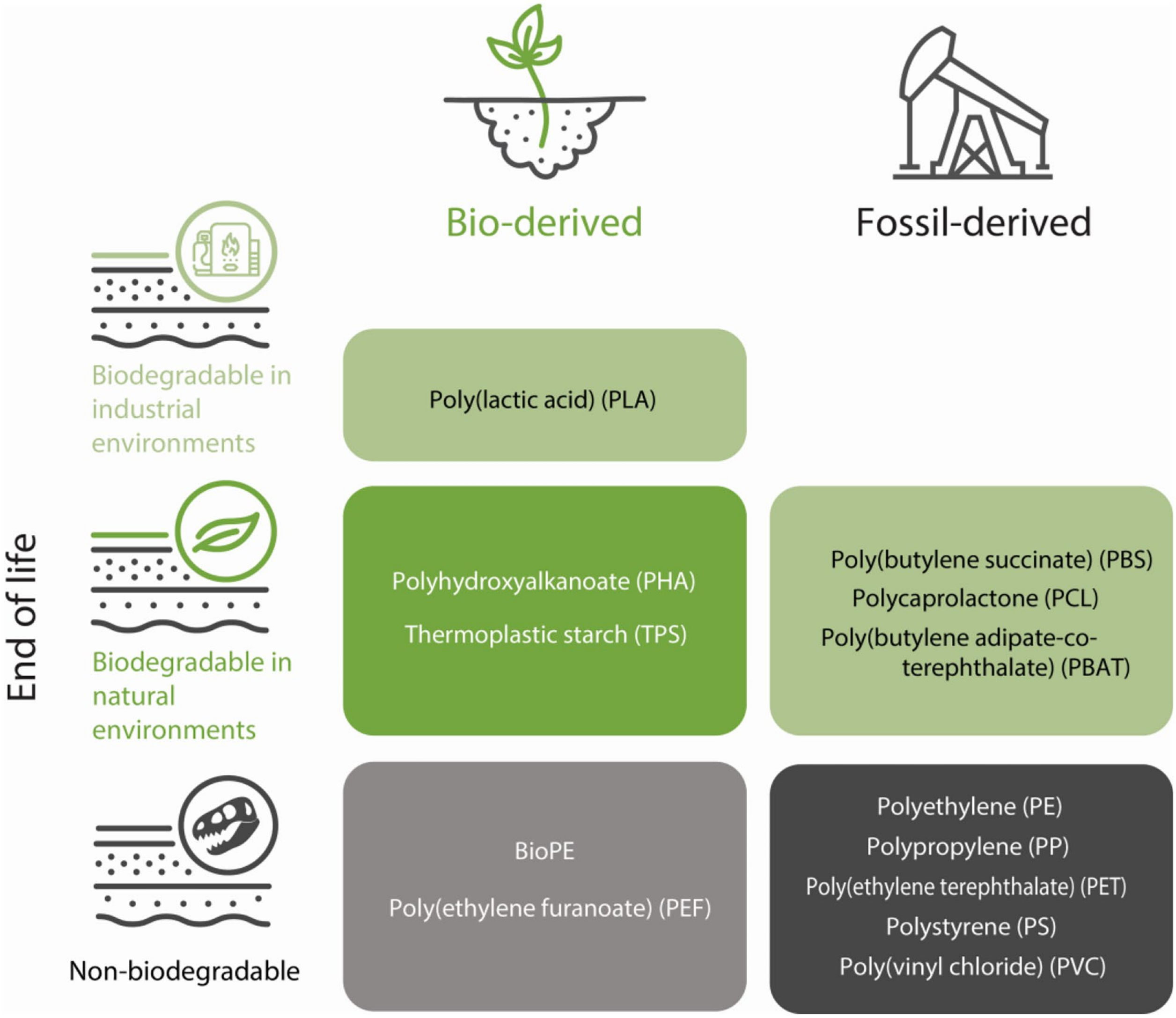

Fig. 4 Polymer classification based on carbon source and biodegradability [31, 32]

Table 3 Properties of selected polymers (where LDPE = low density polyethylene)

Polymer	Density (g/cm^3)	Tensile strength (MPa)	Elongation at break (%)	Elastic modulus (GPa)	Reference
PLA	1.20–1.25	21–63	2.5-6	0.35–3.5	[5, 35]
PHB	1.25	24–40	5–8	3.5-4	[35, 36]
PHBV (1 mol% 3HV)		32.5	8.8	2.6	[37]
PHBV (20 mol% 3HV)		32	50	1.2	[36]
Starch	1.5	5–6	31–44	0.125–0.85	[5, 35]
LDPE	0.910–0.925	40–78	90–800	0.055–0.38	[5]
PP	0.899–0.920	26–42	15–700	0.95–1.77	[5, 36]

Table 4 Hildebrand solubility parameters for a range of polymers (where PBAT is poly(butylene adipate-*co*-terephthalate)

Polymer	Hildebrand solubility parameter ($\text{MPa}^{1/2}$)	Reference
Cellulose	32.0	[40]
Kraft lignin	24–31	[41]
PHB	18.7–19.3	[42]
PLA	20.7 19.9	[43] [44, 45]
PBAT	21.9	[43]
PCL	19.1	[40, 45]
PE	16.6	[40]

properties the matrix is typically much lower in tensile strength and elastic modulus, and often much higher in elongation at break (polymer depending).

Thus, there is inherently a mismatch in performance under load, meaning that good interfacial adhesion (whether physical or chemical) is needed to maintain improved mechanical properties and maintain structural integrity under load. Such biocomposite materials can fail when [12, 38]:

- Tensile forces stretch the matrix more than the fibres, causing the material to shear at the interface between matrix and fibres;
- Tensile forces near the end of the fibres exceed the tolerances of the matrix, separating the fibres from the matrix; and.
- Tensile forces exceed the tolerances of the fibres causing the fibres themselves to fracture leading to material failure.

Overall, the control of the interface is very important for these materials. The Hildebrand solubility parameters (Hildebrand SP) for some biodegradable polymers as well as for cellulose and lignin are given in Table 4, with this parameter being a measure of relative hydrophobicity based on solubilities in solvents, with a lower value indicating that the polymer is more hydrophobic in nature [39]. As can be seen from these results, cellulose has a high Hildebrand SP at 32 $\text{MPa}^{1/2}$, while lignin is intermediate at 24–31 $\text{MPa}^{1/2}$. By contrast, the biodegradable polymers listed all have values in the region of 18–21 $\text{MPa}^{1/2}$, which is less hydrophobic than for polyethylene at 16.6 $\text{MPa}^{1/2}$, but not by a large amount. Thus, while the interfacial adhesion between biodegradable polymers and cellulose fibres is naturally stronger than for many other thermoplastic polymers, the lack of compatibility between the hydrophilic cellulose fibres and the more hydrophobic matrices is still an issue.

In addition, the intrinsic hydrophilicity and high aspect ratio of the cellulosic materials often leads to agglomeration and poor dispersion of the fibres even in biodegradable polymeric matrices [46]. Therefore, the mechanical performance of the biocomposites, as well as their appearance, is impaired [46].

A range of approaches can be taken to modify the interaction between fibres and the polymer matrix to try to improve interfacial adhesion.

In terms of physical methods, these mainly focus on fibre separation as well as surface enhancement. Stretching, calendaring, thermo-treatment or electrical conduction are typical processes here, along with plasma or corona treatment, steam explosion, and laser and gamma ray treatments [10].

Fibrillation is one of the more promising techniques for good matrix-fibre integration, readily delivering increased surface area for interlocking of the polymer with fibre, or fibre with fibre in the case of paper formation [38]. Through mechanical treatment, thermal and mechanical shear forces facilitate the fibrillation of cellulose fibre bundles, in turn partially deconstructing both the crystalline and amorphous regions of the fibre population, leading to a certain reduction in crystallinity [47]. Pennels et al., for example, demonstrated that twin-screw extrusion was a relatively low-energy and effective method for fibrillating a range of nanocellulose fibres from different biomass types, resulting in improved mechanical properties for the resulting nanopapers [47].

Chemical treatment methods can be classified into a range of strategies, from functionalisation of the fibre to modification/functionalisation of the polymer matrix through to the use of coupling agents to chemically bind fibre and matrix together [8]. Some of the typical approaches are summarised in Fig. 5. It should be noted that for some polymer biocomposites, such as for PHA-wood mixtures, the use of interface modifiers actually led to no improvement in mechanical properties, given that the native biocomposite already had excellent inherent properties [48].

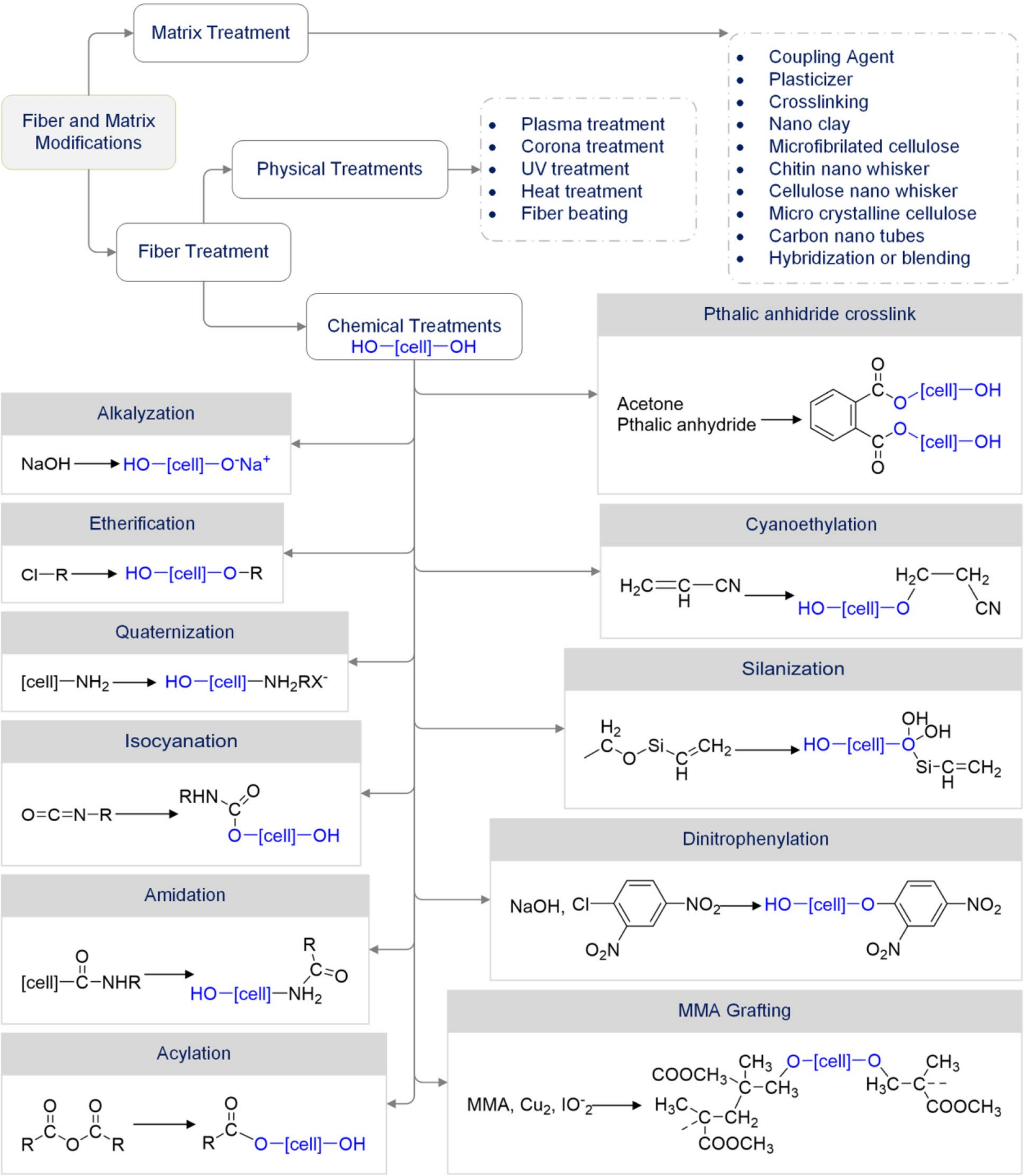

Fig. 5 Approaches used for the modification of lignocellulose materials. Note [cell] is celluloseReprinted with permission from [8]. Copyright © 2022 SAGE Publications

Processing techniques for biodegradable polymer biocomposites

There are many strategies that can be adopted for the production of biodegradable polymer biocomposites, all based on the thermoplastic nature of the polymer matrix. The orientation of the fibres in the resulting matrix plays a critical role in final materials performance, with alignment ranging from continuous unidirectional or bidirectional through to discontinuous aligned, partly oriented and completely randomly oriented, with these different orientations delivering different target properties (Fig. 6) [12]. Within the continuous fibre framework, woven fibres are also commonly used.

High performance biocomposites usually contain fibres as long as the component itself [12]. For such continuous fibres, the use of a thermoforming approach is commonly adopted. More recent techniques are also being developed, such as 3D printing incorporating continuous fibres either by merging the continuous fibres in the printhead with the surrounding thermoplastic matrix and then depositing them on the print bed or by pre-impregnating continuous fibre filaments in the thermoplastic matrix and immediately extruding [49]. For short- and long-fibre reinforced biocomposites, the most commonly used processes overall are compression moulding, injection moulding, and extrusion. For long fibre materials (longer than 2 mm and preferably > 5 to 25 mm), the use of thermoforming, compounding and long fibre thermoplastic-direct methods can also be adopted [10]. In all cases, the appropriate selection of temperature profiles to deliver good wetting while avoiding thermal degradation is particularly critical for biodegradable plastic matrices. For melt extrusion processes, the correct screw profile and optimised feed operating conditions must also be designed to maximise integration.

Mechanical properties of biodegradable polymer biocomposites

These biodegradable polymer biocomposites exhibit superior material properties, which in most cases the traditional engineering materials (e.g., metals) cannot provide at low weight. As already noted, they typically have high tensile and flexural modulus. It is not possible to provide an exhaustive list of material properties of such biodegradable polymer biocomposites that have been produced in this article. For that, the reader is referred to some recent reviews (see [5, 6, 8, 10] for example). Only a subset of biocomposite materials – wood-fibre biocomposites - is shown here in Table 5.

A snapshot of some of the factors that affect mechanical properties of biocomposites is provided in Fig. 7, with additional factors including the use of plasticisers, and temperature and force applied during processing. Further, the presence of waxy materials in the fibre can affect the interfacial adhesion and wettability of the biocomposites.

Finally, in terms of optimising the properties achievable from biodegradable polymer biocomposite materials, there is a strong move now towards integrating a machine learning framework into biocomposite production under an industry 4.0 scenario, as shown in Fig. 8. This approach cycles through a process of data accumulation and optimisation of material properties, through an integrated feedback loop with data accumulation and model training, assessment and validation to lead back to

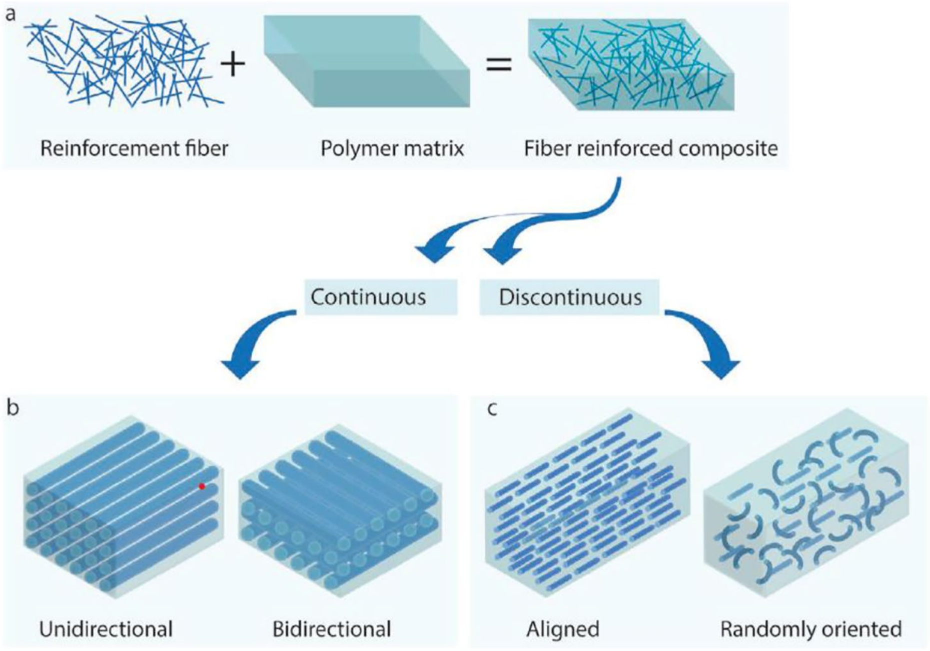

Fig. 6 The structure of a fibre reinforced biocomposite: (**a**) Basic constituents; (**b**) continuous fibre reinforced biocomposites (unidirectional and bidirectional); and, (**c**) discontinuous fibre reinforced biocomposites (aligned and randomly orientated) [12]. (Reproduced under Creative Commons CC-BY)

Table 5 Typical range of tensile properties of biodegradable polymer based wood-plastic composites, in comparison to PP- and high-density polyethylene (HDPE)- wood plastic composites (all with wood contents of 40–50%). Modified with permission from summary presented in [2]. Copyright © 2022 Taylor & Francis

Biocomposite type	Tensile strength (MPa)	Tensile Young's modulus (GPa)	Elongation at break (%)
Wood-PHA	13–26	0.5–5.9	0.5–6.6
Wood-PLA	37–71	1.2–8.9	1.0-3.1
Wood-starch	14–36	0.7–4.8	1.1–2.9
Wood-PP	18–47	1.8–5.6	1.6–5.4
Wood-HDPE	12–39	0.8–4.7	1.4–2.9

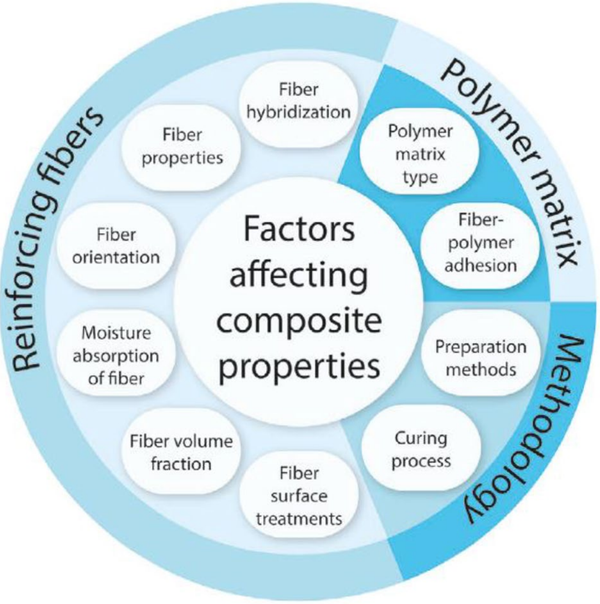

Fig. 7 Factors that influence the mechanical properties of fibre reinforced plastics [12]. (Reproduced under Creative Commons CC-BY)

more materials development, data accumulation, model refinement and so on [50]. With the aim being to deliver more rapid materials development as well as to develop robust structure-property relationship mapping, leading to robust materials development.

Durability, biodegradability and recycling of biodegradable polymer biocomposites

Given the inherent biodegradability of these materials, there can be some concern over in-use durability. In this case, particularly for biocomposites that are exposed to the open environment, the durability under exposure to natural weathering conditions like humidity, temperature, rainfall and UV irradiation, given also that there is associated cycling of this exposure, needs to be assessed. There are a wide range of factors that can affect lifetimes in use, including microbial attack (fungi, bacteria etc.) as well as moisture absorption, thermal stability, UV resistance and flame retardancy [10]. Moisture absorption in particular is associated with preferential swelling of the organic fibre, leading to differential expansion between matrix and fibre and delamination of the interface. This is particularly the case when there is cycling of this moisture uptake (shrink/swell cycles). Durability under practical use in dynamic rather than static applications, with varying loads and stresses, is also an area where more research and practical in-use testing is required.

Thermal stability is less of an issue under ambient conditions, and more of a concern during processing, where some degradation of material properties can occur for biodegradable polymer matrices in particular. For many applications, some fire retardancy is important, given that both natural fibres and biodegradable polymer matrices are inherently flammable. If required, this can be controlled through the use of additives such as phosphates or metal hydroxides.

The sensitivity to UV degradation from ambient solar radiation is highly variable and matrix and environment dependent for biodegradable polymer biocomposites. As noted in Laycock et al. [51], it is important that any testing of these materials is performed under either natural weathering conditions or, if accelerated testing is required, that natural sunlight simulators are used. There are very different UV absorption profiles for polymers that contain aromatic groups, such as poly(butylene adipate-*co*-terephthalate) (PBAT), which degrades via a free radical promoted crosslinking process, compared to aliphatic polyesters such as PLA, which undergoes degradation via both chain scission and chain recombination rather than cross-linking [51]. In terms of composites, natural fibre composites have been shown to surface oxidise under UV exposure, leading to thermal and mechanical stresses on the surface and inner part of the biocomposites, resulting in stress concentration and shrinkage, reducing overall performance [52]. However, there is some evidence [53] that biodegradable polymer biocomposites such as PHA-wood are robust to outdoor weathering, performing similarly to polyethylene-wood composites, and also that such materials are very robust and durable in an indoors setting [54, 55].

In terms of biodegradation, there is again inherent variability depending on the biodegradable polymer matrix.

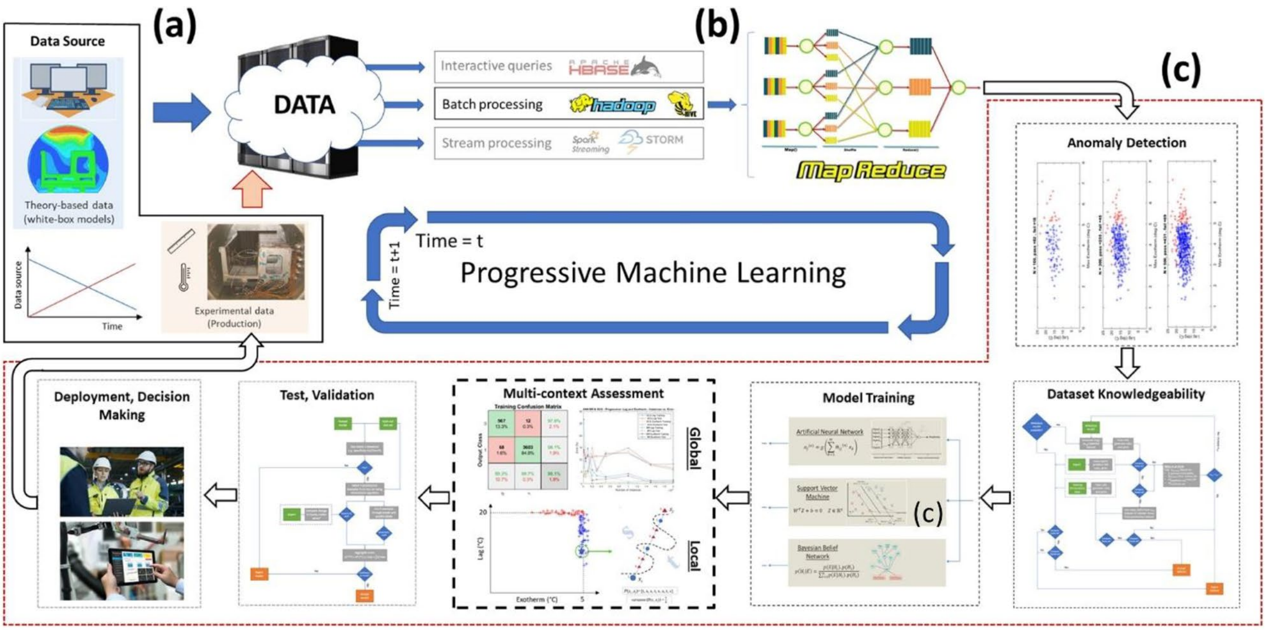

Fig. 8 An Industry 4.0 framework for polymer biocomposites, reprinted with permission from [50]. Copyright © 2021 Elsevier

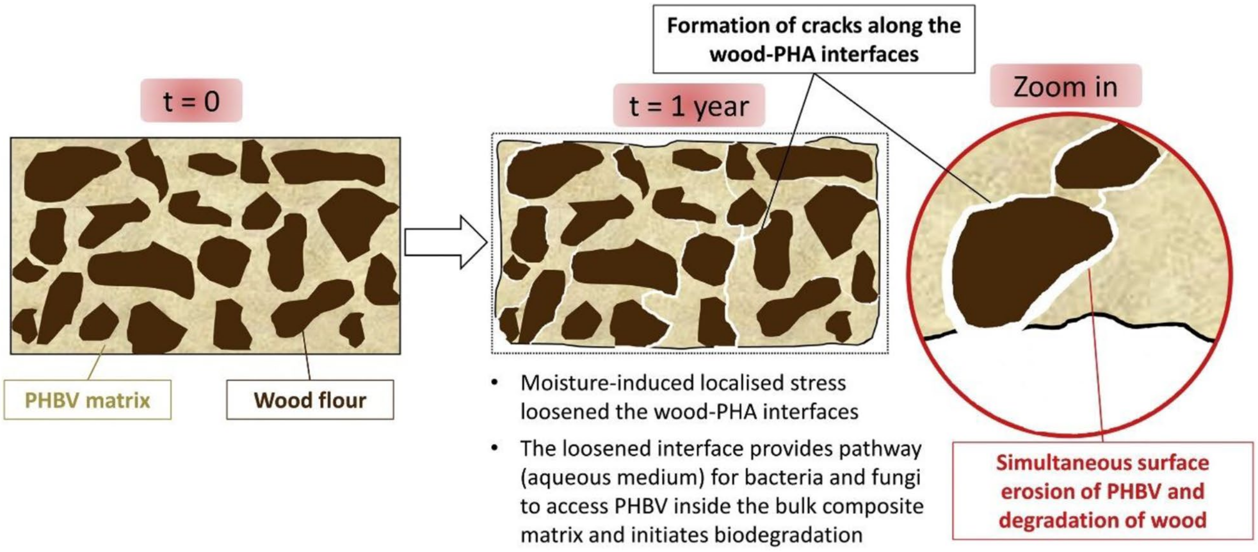

Fig. 9 Influence of wood flour on biodegradation of PHBV. Reprinted with permission from [37]. Copyright © 2019 Elsevier

As previously noted, PLA primarily undergoes abiotic hydrolysis via bulk erosion, which is a slow process under ambient conditions. Thus, the biodegradation rate of PLA-based biocomposites is slow, although somewhat accelerated by the presence of the hydrophilic fibres, which accelerates the process. By contrast, the biodegradation of biocomposites based on polymers such as PHA, which degrade via a much faster biotic (enzyme catalysed) surface hydrolysis under ambient conditions, is significantly accelerated by the presence of the hydrophilic fibres. In this case, there are a combination of processes at play, such as moisture cycling and water ingress along the hydrophilic fibre, creating localised stresses and loosening the interface, providing a pathway for bacteria and associated enzymes to access the bulk of the polymer (Fig. 9).

Some biodegradable polymers such as PHAs are very readily digestible under anaerobic conditions, being rapidly converted to methane which can then be captured and used as an energy source, converting in turn to CO_2, which is ultimately recycled back into organic feedstock – a form of circularity, at least with respect to the carbon.

By contrast, other biodegradable polymers, such as PLA and, in particular, PBAT, are very slow to degrade under such conditions [56]. Within an industrial composting environment, on the other hand, most biodegradable polymer biocomposites will meet the composting requirements, although the time to complete biodegradation to CO_2 and water is of course dependent on form (thickness, mass, surface area exposed etc.) as well as the compost conditions (temperature, microbial community richness, oxygen, and so on).

The mechanical or chemical recycling of biodegradable polymer biocomposites is an active area of investigation for which there is far less research to date [57]. Biodegradable polymers and their biocomposites are known to be less stable to remelting and reprocessing, showing strong degradation after limited cycles. Chemical recycling back to starting monomers, oligomers or other chemicals is a growing area of research, although in composite form it will be much more challenging to separate and isolate the fibres from the matrix in order to achieve good conversions [57]. Incineration, or the combustion of biocomposites to produce energy and CO_2, is the last conversion option in terms of end-of-life management for these materials, given that they have high heat of combustion [58]. Finally, landfill is a common fate for much of the plastic waste currently generated. For biodegradable polymer biocomposites, the ultimate fate in a landfill scenario is to produce methane, so that the efficiency of methane capture from such facilities has a strong role in determining the environmental impact of this path. It should be noted that the effects of additives and processing aids on these processes will likely be significant and is also an active area of research.

Overall, thorough life cycle analysis has to be performed to assess the environmental impact of this new generation of material. These challenges are now being addressed, with current investigation seeking to deliver a thorough understanding of the whole process from raw materials to end-of-life properties as well as technologies to address the compatibilisation and stability issues identified above.

Conclusions

The development of new biobased and biodegradable polymer biocomposites is an active area of research and shows great promise to produce more sustainable products – based on the holistic product value chain of supply, processing and end-of-life. Importantly, the current challenges associated with the use of biofibres mixed with biodegradable polymer composites, such as inadequate fibre-matrix adhesion, moisture absorption, control over fibre orientation, need for increased toughness, and improved fire resistance, are being addressed. In solving these challenges, there is strong promise seen for these materials, such as in improved mechanical properties, improved processing performance and lower processing energies, along with the associated benefits of reduction in the use of non-renewable polymers and biodegradation at end of life. Underpinning the delivery of this promise will be fundamental understandings in polymer chemistry, processing, and structure-property-degradation relationships.

Authors' contributions

BL wrote the main manuscript text. BL, SP and PH reviewed the draft and added material. All authors agered on final changes to the manuscript.

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Declarations

Ethical approval

Not applicable.

Competing interests

The authors declare no competing interests.

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