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Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends

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ABSTRACT

Biocomposites being environmentally-friendly alternative to synthetic composites are gaining increasing demand for various applications. Hence, biocomposite development should be integrated within a circular economy (CE) model to ensure a sustainable production that is simultaneously innocuous towards the environment. This review presents an overview of the state-of-the-art technologies for the adoption of the CE concept in biocomposite development. The study outlined the properties, environmental and economic impacts of biocomposites. A critical review of the life-cycle assessment of biocomposite for evaluating greenhouse gas emissions and carbon footprints was conducted. In addition, the opportunities and challenges pertaining to the implementation of CE have been discussed in detail. Recycling and utilisation of bio-based constituents were identified as the critical factors in embracing CE. Therefore, the development of innovative recycling technologies and an enhanced use of novel biocomposite constituents could lead to a reduction in material waste and environmental footprints. This article is one of the first studies to review the circularity of biocomposites in detail that will stimulate further research in enhancing the sustainability of these polymeric materials.

1. Introduction

1.1. Plastics and environment

The global concern over depleting fossil fuels as well as the gradual increase in plastic waste and carbon footprint of products have heightened the interest in the usage of alternative environmentally friendly materials [1]. Most plastics are created from synthetic organic solids containing petrochemicals acquired from fossil-based fuels [2]. The value of the global consumption of plastics was rated at USD 568.9 billion in 2019 and is estimated to increase by 3.2% annually in the next seven years [3]. Although plastics are cheap and have desirable long-lasting properties, after their end-of-life, they accumulate as waste in landfills and oceans. According to the predictions made by environ-

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Abbreviations: ABS, Acrylonitrile butadiene styrene; CE, Circular economy; C2C, Cradle-to-cradle; C2F, Cradle-to-factory; C2G, Cradle-to-grave; EFB, Empty fruit bunch; EoL, End-of-Life; EU, European Union; FRCs, Fibre reinforced composites; GWP, Global warming potential; GHG, Greenhouse gas; HDPE, High-density polyethylene; IACMI, Institute for Advanced Composites Manufacturing Innovation; LCA, Life-cycle assessment; LDPE, Low-density polyethylene; PVC, Poly vinyl chloride; PHBV, Poly(3-hydroxybutyrate-co-3-hydroxyvalerate); PE, Polyethylene; PET, Polyethylene terephthalate; PHA, Polyhydroxyalcanoates; PLA, Polylactide; PP, Polypropylene; PS, Polystyrene; SSDR, Specific surface degradation rate; TPS, Thermoplastic starch; VOCs, Volatile organic compounds; WLB, Waste leather buff.

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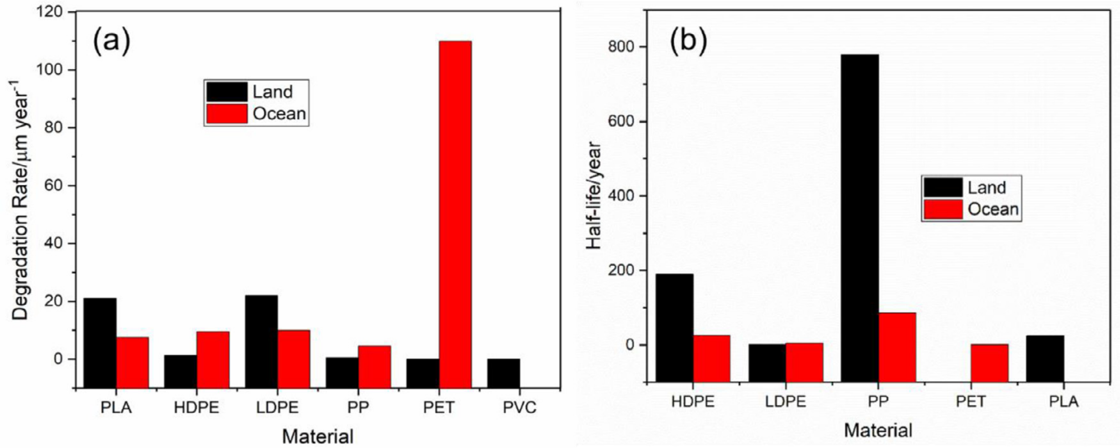

Fig. 1. (a) Degradation rate of common plastics, (b) Half-lives of common plastics. Figure drawn based on data from Ref. [6].

mental scientists, the global plastic waste in landfills will be around 12,000 million tons by the year 2050 [4]. The annual generation of plastic waste is reported to be about 400 million tons with almost half of the amount generated from packaging. Out of the 400 million tons, 150 million tons end up in the world's oceans [3]. Plastic waste has a slow degradation rate due to its chemical composition, structure and the addition of antioxidants and stabilisers, mostly to extend the lifespan of plastics [5]. It is very evident that the same properties that give plastics desirable attributes are responsible for the threat they pose to the environment. Chamas et al. [6] studied degradation rates and half-lives of typical plastics commonly occurring in the waste stream (polyethylene (PE), polystyrene (PS), poly vinyl chloride (PVC), polypropylene (PP) etc.). The authors introduced specific surface degradation rate (SSDR) as a variable for measuring the mass loss rate of plastic waste. The SSDR values and half-lives calculated for some of the plastics are shown in Fig. 1. According to their research, the degradation rates of plastics exposed to ultraviolet rays or heat was faster compared to buried plastics in both land and water. However, while some plastics (polylactide (PLA), low-density polyethylene (LDPE)) degraded faster on land others like high-density polyethylene (HDPE) and PP had accelerated degradation rate in ocean. Furthermore, the half-lives of plastic wastes on land were higher than in ocean.

It is worth noting that the decomposition of plastic materials results in the release of noxious chemicals that is a potential threat to the environment and extremely harmful to human health [7]. Tommaso et al. [8] investigated the volatile organic compounds (VOCs) released from the degradation of conventional plastic wastes. The authors found out that the quantity of compounds released from the plastics after four weeks of ageing was dependent on the type of plastic. The volatile products collected from the degradation process of PP, PE, PS and polyethylene terephthalate (PET) were ketones, lactones, esters, carboxylic acids, aldehydes, alcohols and ethers as well as non-functionalised aromatics. The total amount of oxygenated compounds from these plastics are illustrated in Fig. 2. The analysis showed that PP emitted the highest amount of volatile chemicals within the four-week interval. Royer et al. [9] stated in their work that the release of noxious chemicals from plastic waste into the atmosphere will continue as long as there is an exposure of the materials to sunlight and heat.

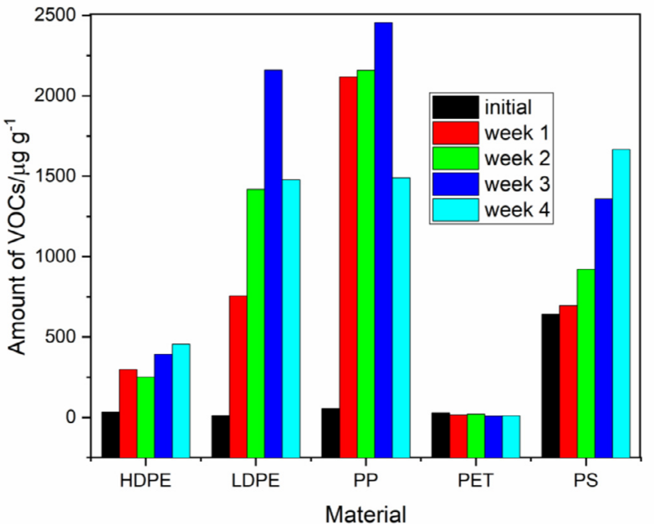

Fig. 2. Total amount of oxygenated chemicals from typical plastic degradation. Figure drawn based on data from Ref. [8].

Apart from the toxic chemicals, microplastics generated from the degradation of long-chain polymers have an adverse effect on humans and the environment [10,11]. During degradation process, the plastic waste undergoes chemical processes such as oxidation, diffusion or random chain scission, and crosslinking. These actions result in the brittleness and fragmentation of the plastic till a lower molecular weight is achieved for further metabolism by microbes [12]. Marine organisms can consume microplastics, which may carry additives thereby contaminating the food chain [13]. Microplastics also contribute immensely to the emission of greenhouse gases and cause pernicious climate change [14]. Hale et al. [15] determined the composition of microplastics, transportation, metabolism and their impact on the environment. Sampling, identifying the additives in the microplastics and characterising the reactions that will occur in an extended period are some of the challenges the authors encountered in their research. By analysing the progress of impact of microplastics in the soil, Wang et al. [16] discovered that microplastics could alter the soil structure, water-retaining ability and nutritional content, which will consequently affect plant growth negatively. From the aforementioned discussion, it is clear that the utilisation of petroleum-based plastics and synthetic materials for polymeric materials development is pernicious towards the environment. This necessitates the employment of sustainable materials that are concurrently renewable and are innocuous towards the environment. However, continued use of bio-based resources is not a sustainable solution either and to propagate the beneficial effects of biocomposites over the synthetic counterparts, the entire production system must be rendered sustainable. Circular economy (CE) concept can facilitate the attainment of such sustainability by encouraging the utilisation of bio-based materials that can be readily recycled and reused. However, a comprehensive review about the various facets of CE that can affect bio-

Table 1
Tensile strengths and moduli of biocomposites fabricated with various biofillers.

Matrix	Bio-reinforcement	Tensile strength (MPa)	Young's modulus (GPa)	Reference
Polycaprolactone	Date palm leaf sheath (20 wt.%)	25	0.279	[34]
Poly (butylene succinate)	Apple pomace (40 wt%)	32	1.5	[35]
PLA	Cork (30 wt%)	25	0.85	[36]
Polyhydroxybutyrate-co-hydroxyvalerate	Cork (30 wt%)	21	1.012	
Poly-e-caprolactone	Cork (30 wt%)	16	.375	
Starch-poly-e-caprolactone	Cork (30 wt%)	18.5	.362	
TBS	Bacterial cellulose (22 wt.%)	31	.361	[37]
PLA	Cellulose nanocrystals (20 wt%)	-	2.6	[38]
PP	Egg shell (20 wt.%) and talc shell (20 wt.%)	-	2.6	[39]
PP	Shellfish shell (10 wt%)	33	1.5	[40]
Soya flour	Jute fibre (50 wt.%), cellulose whiskers (5 wt.%) and nanoclay (3 wt.%)	52.5	2.363	[41]

composite manufacturing, performance properties and use is lacking in the current literature. Hence, this review article discusses the attributes of CE with respect to biocomposite development.

1.2. Bioplastics/biocomposites

The non-degradable nature of synthetic plastic waste in the ecosystem has led to an increase in the research on more eco-friendly materials [17–19]. In this vein, environmentally compatible solutions such as biocomposites have been developed [17–20]. The added advantages of recyclability, lightweight nature and cost-effectiveness make biocomposites an interesting area for researchers [18,19,21]. Biocomposite constituents such as bio-based polymers and fillers are obtained from renewable natural sources and can serve as a possible replacement for oil-based non-renewable plastics [22–25]. Biocomposites have less environmental footprints, hence, they are safer for humans and other living habitats [26,27]. Furthermore, most biocomposites are recyclable and reusable. Joshi et al. pointed out one of the most important advantages of biocomposites as having a manageable end of life disposal potential [28]. Sheldon et al. [29] classified raw materials of biocomposites into two groups, first-generation and second-generation materials. First generation raw materials are wood, and their use in larger quantities can lead to deforestation and affect biodiversity, whereas second-generation raw materials are lignocellulosic wastes collected from food, forest and agricultural residues. Until now, second-generation waste has largely been used for the development of biocomposites, although their commercialisation is still limited. Extended research in the area of biocomposites has led to the development of different types of biocomposites, yet the synthesis and development of these materials are not fully commercialised and their applications are low [30]. Acknowledging the processing methods, preparation of biocomposites and their application in different sectors could globally reduce the use of oil-based plastics [31,32]. Biocomposites can be produced from available plastics (PE from bioethanol through bioethylene) or can be developed from renewable natural sources (PLA from corn starch) [29]. In addition, biodegradability in oil-based plastics composites may also be increased by the reinforcement with biofillers. The addition of biofillers can increase the strength (in conjunction with a coupling agent) and modulus of a polymer and at the same time enhance the biodegradability of the entire composite system. Table 1 shows the tensile strength and modulus of some biocomposites reinforced with biofillers. Some polymeric matrix and fillers used for the fabrication of biocomposites are shown in Fig. 3.

Most of the biowaste reinforced composite investigations targeted the mechanical and thermal properties [42–47], hence, there is an opportunity to study the recycling, reuse, biodegradation and environmental impacts of such biocomposites. A detailed investigation into these subjects could facilitate the circularity of the composites and benefit both the environment and the economy.

1.3. Bioplastics and circular economy

In light of the aforementioned challenges, several measures have been put in place to minimise the use of plastics globally and also to consider incineration and recycling as viable strategies for reducing plastic waste [48]. However, plastic incineration has major drawbacks including water and air toxicity owing to the significant harmful chemicals and ash waste residue released into the atmosphere during the process [5,49–51]. To boost energy production, which is the key advantage of incineration, depleting fossil-based fuels like coal are utilised to supplement plastic wastes. Incinerators for commercial applications operate at an estimated cost of USD 5-53 billion per year and still fail to eliminate plastic wastes in the system. Recycling of plastics, though effective, presents challenges in relation to plastic identification, collection of recyclable waste, sorting of plastics to prevent phase separation during melting and concerns over the preference of virgin plastics to recycled ones [52]. One plausible solution is the use of bio-based plastics and composites. Bio-based plastic and composites could replace non-degradable polymers that create environmental problems. Bio-based materials, such as agricultural and forestry waste, can be used as reinforcement/filler for the development of biocomposites [53]. These materials are renewable and biodegradable and hence can be a suitable alternative to fossil-based materials. In addition, the production of bio-based plastics and composites ensures the proper utilisation of biomass wastes. The demand for bio-based plastics and composites is projected to increase at a compound annual growth rate of 11.2 % over the forecast period, i.e. 2017-2030 [3]. This demand can be met by the recycling of bio-based plastics and composites. Fig. 4 depicts how the concept of recyclability can be utilised for biocomposites.

The increasing demand for the use of natural resources in biocomposites manufacturing exemplifies the need for a CE in biocomposites that also allows for their recycling and reuse [55]. The main objective of CE is to maintain sustainability by minimising waste and maintaining resources at their highest value [56]. Although the concept of CE is concerned with reducing the carbon footprint at every stage of a product's life cycle, one way to integrate the concept is to use wastes for the development of composites that will somewhat avert the take – make – use – dispose mindset currently rampant in the contemporary society [57,58]. Adaptation of the CE in biocomposites improves their recyclability, reusability and convert biocomposites waste into useful products, energy or secondary materials, which could lead to a reduction in biocomposites waste landfilling [59]. Furthermore, converting waste into value-added products would close the door to discards, which would ensure the continuous use of raw material inputs in a CE that would allow the conservation of the resource value [60,61]. However, adoption of a CE in biocomposites is challenging due to the inherent bonding of the matrix and filler/reinforcement, which makes their separation difficult and costly [61]. Adapting circular practises such as design, repair, re-use and re-cycle [62] in composite manufacturing and developing appropriate technologies could help to achieve circularity in biocom-

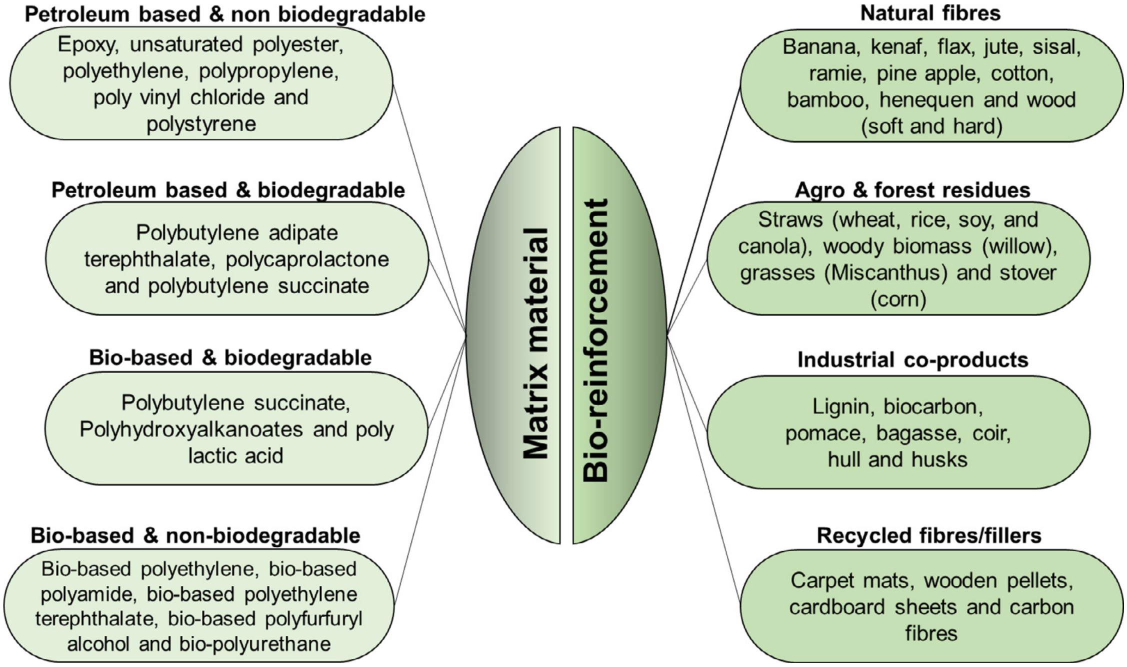

Fig. 3. Some matrix and fillers used for the fabrication of biocomposites. Figure drawn based on data from Ref. [33].

Fig. 4. Recyclability of biocomposites. Figure drawn based on data from Ref. [54].

posites. Some efforts have been made to adapt CE for biocomposites. For instance, the Institute for Advanced Composites Manufacturing Innovation (IACMI), Knoxville, Tenn., U.S. has taken necessary steps to adapt circularity in composites for recycling and reusing fibre wastes [63,64]. It has been reported that carbon fibre recovery from composites consumes 15 % less energy than what is required for the production of virgin carbon fibres [63,64]. All of these benefits can be attained for biocomposite development by employing CE concepts. Fig. 5 shows the phases of a CE model for composite materials.

There are three main factors in attaining CE in biocomposites: using bio-based raw materials (i.e., bioplastics and bio-based fillers); recycling and Life cycle assessment (LCA) to determine greenhouse gases (GHG) emissions and carbon footprints of the developed composites. In this light, this review article details the opportunities, challenges and importance of maintaining CE in biocomposite materials. In addition, effect of bioplastics and bio-reinforcements on environmental impacts, recyclability of biocomposites as well as LCA assessment for biocomposites are also discussed. At present, there is no comprehensive review

Table 2
Comparison of plastic recycling methods.

Recycling method	Mechanical recycling	Chemical recycling	Thermal recycling
Advantage	Cheap process, efficient, less CO_2 emissions.	Enables production of high-quality end products, dyes and other contaminants can be removed from waste plastics.	Used for energy production, reduced fuel cost in energy generation.
Disadvantage	Pre-treatment needed, deteriorate the plastic properties.	Cost-intensive, pre-treatment needed, chemicals/catalysts are needed.	Environment pollution.

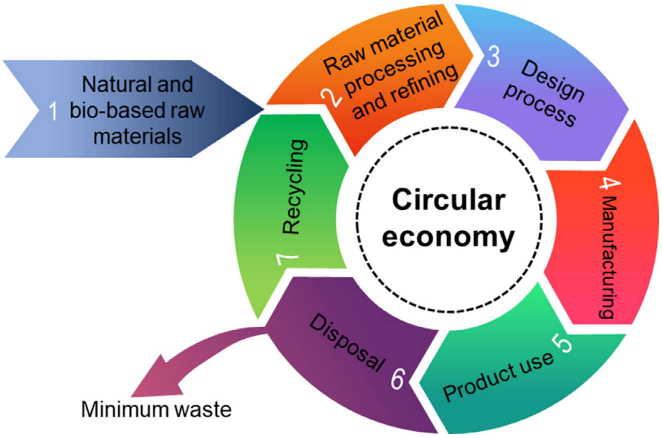

Fig. 5. The different phases of the CE model. Figure drawn based on data from Ref. [65–67].

article on the concept of CE of biocomposites and as such, the current paper aims to bridge this gap.

2. Recycling of bioplastics/biocomposites

The different recycling methods associated with bioplastics/biocomposites can be broadly classified into three types, a) mechanical recycling, b) chemical recycling and c) thermal recycling or processing [65,68,69]. Numerous extrusion/injection cycles are performed to re-melt and then simultaneously re-mould bioplastics/biocomposites in mechanical recycling methods. In general, for the mechanical recycling process, plastics are cut, shredded and converted into granules, pellets or flakes of adequate quality and then extruded to produce the new product. During extrusion, virgin plastics are also added to increase the quality but the repeated mechanical recycling process causes the properties to deteriorate due to the lower molecular weight of recycled plastics [70] or the reduction of aspect ratio in the reinforcements. Thus, it is to be kept in mind that recycling can be performed up to a certain point, which is still environmentally beneficial than one-time use plastic materials. In chemical recycling processes, a suitable solvent is selected for the matrix polymer and is then subsequently dissolved in this solvent followed by the separation of reinforcing material from the matrix [68,71]. Through chemical recycling process, plastics are converted into monomers or partially depolymerized to oligomers utilising chemical reactions. Some of the chemical reactions used in decomposing polymers into monomers are thermal cracking, microwave degradation, hydrogenation, methanolysis, glycolysis, chemical depolymerisation, gasification, pyrolysis, photodegradation, ultrasound degradation, catalytic cracking and reforming and hydrolysis [70]. On the other hand, energy recovery by means of incineration or combustion is the major aspect in thermal recycling processes. This is a promising solution because it generates significant energy from polymers but is not environmentally safe due to the generation of toxic airborne substances that are harmful to health [70]. Table 2 compares the characteristics of these three recycling methods. Among the three categories, mechanical recycling methods are considered to be the most successful recovery or recycling methods owing to the advantages like processing ease, comparatively low cost, and most importantly the ability of the user to control the technological parameters [69,72]. The major bottleneck in applications for recycled composites is that the recovered material should be in flawless condition in order to be re-used, which places a high demand for the non-destructive testing and recycling of the said material. Additionally, the possible application areas are much limited, in most cases, the individual components that have been recovered can be re-used only in applications which are virtually the same. In the case of thermoplastic polymers, extrusion can be effectively utilised to process the ground or chopped material and if deemed necessary additional reinforcements can also be added during this processing to enable specific applications. In fibre reinforced biocomposites, depending on the process control, shortening of the fibres in the material will take place during the grinding process. These fibres can still be utilised as a reinforcing or filler material depending on the resulting properties.

In principle, composite recyclates are not excluded or barred from being utilised in any applications including that of food packaging, however, their uses are governed by strict quality control aspects of the recyclates and the method by which the material is recycled. In addition to these conditions, the recyclates need to adhere to strict safety regulations like the European Union (EU) regulations 89/109, 90/128, 92/39, etc. [73]. The obtained recyclates could be used to prepare composites that can be further recycled several times. However, this would depend on the number of maximum recycling processes that can be bestowed upon a material until it affects the reinforcement properties completely with regards to the required size reduction post-treatment. However, it should be clearly noted that highly structural applications are unlikely to incorporate the use of recycled materials in the system, and for such applications new composites are a must.

3. Properties of recycled biopolymers/biocomposites

The recycling process of composite materials is on the right track, however, in order to make it more commercially viable more challenges are to be overcome. Research and innovation in this area has just begun that helps to understand the properties of the recycled materials and hence there is a vast sea of opportunities for everyone involved [74]. Chaithanya et al. [69] has recently reported the recyclability studies of biocomposites fabricated from PLA as the matrix and sodium bicarbonate treated sisal fibres as the reinforcement. In this work, the extrusion process was utilised for the recycling studies and the biocomposites were recycled for a total of 8 times. It was observed that after the third cycle the samples demonstrated a severe reduction in the dynamic mechanical properties (storage and loss modulus). The recycling process also led to extensive fibre and matrix degradation as evidenced by morphological and thermal studies. The major factor contributing to the degradation process of PLA was found out to be hydrolysis. The authors concluded that the recycling of PLA/sisal biocomposites is not recommended above three cycles and samples that have been recycled up to three cycles can be used in low to medium strength non-structural applications [69]. Xu et al. [75], on the other hand, studied the recycling capability of carboxymethyl chitosan incorporated epoxidised natural rubber biocomposites. The recycling capability was studied by chopping the tensile samples of carboxymethyl chitosan incorporated epoxidized natural rubber biocomposite into small pieces and then directly moulding at 100 °C for a duration of 5 min. Once the tensile analysis of these

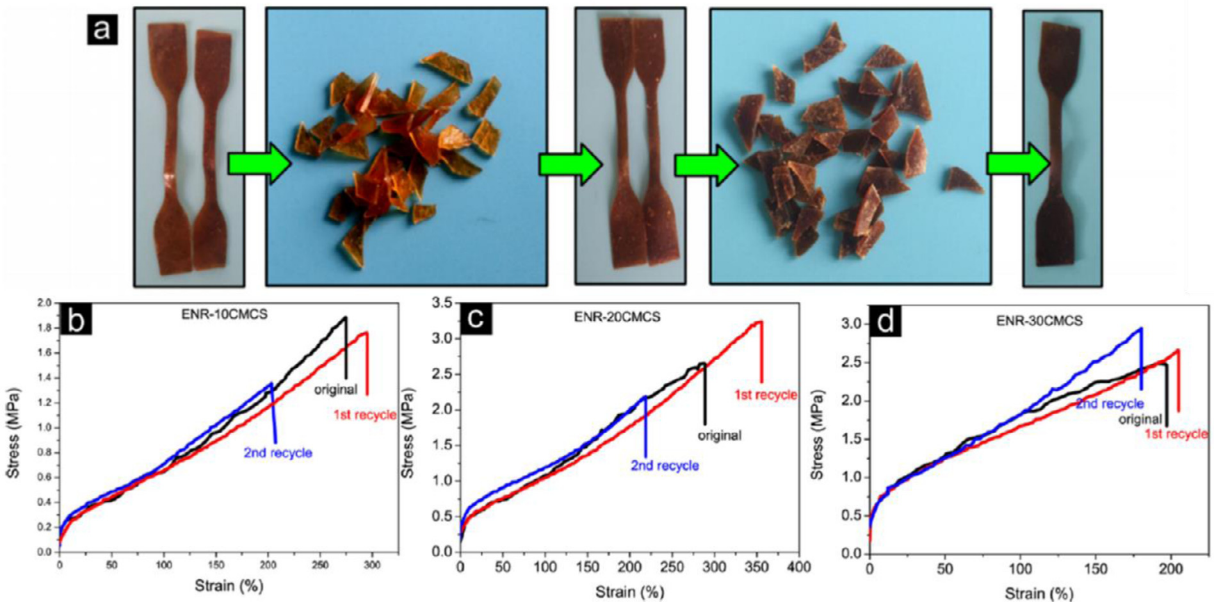

Fig. 6. (a). Representation of the recycling process, (b, c & d) Stress-strain curves of epoxidised natural rubber/carboxymethyl chitosan biocomposites with 10, 20 and 30 wt % filler, respectively. Reproduced with permission from [75], Copyright © 2019 American Chemical Society.

samples was completed, the stretched samples were then again chopped into small pieces for the next recycling process. It was noted that after two recycling, the sample appeared to be getting darker and rougher probably due to the degradation of carboxymethyl chitosan and hot-pressing induced ring-opening of epoxy groups. The recycled samples became darker and harder after the third cycle, possibly as a result of significant oxidative degradation of carboxymethyl chitosan [75]. It was observed that after three recycling process, the samples demonstrated a decrease in their tensile performance (Fig. 6). It was concluded that the several moulding processes during the recycling may lead to additional covalent cross links within the supramolecular hybrid network. These additional cross links could possibly compensate for the deterioration in mechanical performance as a result of changes to the original structure due to recycling processes.

In a similar work, Xu et al. [76] reported that even though conventional cross-linking of rubbers leads to better mechanical properties for the material, the disadvantage of this process is that it makes them thermosets with no chance of recycling and losing the self-healing ability. The current sustainable needs of the society thereby require these two attractive properties to be integrated with these cross-linked rubbers. In order to attain this Xu et al. [76] modified bentonite clay using citric acid and was later incorporated into epoxidised natural rubber. The presence of several carboxyl groups on the clay surface acted as the cross-linking moiety to covalently cross-link epoxidised natural rubber by means of beta hydroxyl ester linkages. The thermally activated transesterification reactions caused the dynamic shuffling between modified bentonite and rubber chains. The peculiar vitrimer-like behaviour is the reason behind the successful recycling of these rubber composites (which is otherwise not possible) and the probable mechanism of recycling is by means of network topography rearrangement during the above-mentioned transesterification reactions [76]. The recycling studies were performed by cutting the tensile samples into small pieces and then compression moulding at 200 °C for 5 min holding time. It was observed by Xu et al. [76] that after the first recycling process, approximately 95 % of the tensile properties were retained. However, it was also observed that with increasing recycling times the mechanical properties started to decline as a result of irreversible covalent cross-linking from the self-crosslinking of rubber chains. Nonetheless, as a final statement, it can be said that even after multiple recycling cycles, the rubber composites were able to recover a large proportion of the mechanical properties [76]. Table 3 depicts a comparative display of few works in which the mechanical properties of recycled biocomposites are demonstrated.

The mixing of biopolymer matrix with natural fibres or materials like starch/chitosan/chitin etc. leads to composites in which both the matrix and the reinforcement are derived from renewable resources and hence are compostable in nature, which makes these biocomposites very attractive replacements for glass and carbon fibre reinforced petrochemical-based polymeric composites [80]. In addition to the above advantages, the capability to be recycled makes these materials more interesting owing to the extension of their respective life cycles and thereby leading to the reduction of the global impact on the environment by the decreased consumption of raw materials. Several researchers have reported successful and effective recycling of flax fibre reinforced PLA based biocomposites by means of mechanical processing [81–83]. Their studies revealed that flax/PLA composites that are compostable have been found to have identical mechanical properties to that of glass fibre/PP, hemp/PP and sisal/PP composites. The interesting observation was that even after three injection cycles, the tensile properties of the PLA/flax composites were retained at different fibre contents. In general, the authors concluded that even though the recycling or reprocessing leads to a decrease in molecular weight, fibre length and separation of the fibre bundles, it did not have a significant detrimental effect on the mechanical properties even after three cycles and hence were considered to be promising results with respect to recyclability of the biocomposite [83]. Another method of recycling that has been employed by researchers is grinding of a biocomposite and then using it as a reinforcement. The potential of this method was evaluated by Grozdanov et al. [84] where biocomposites made up of PLA/rice husk/kenaf fibre was ground and then reused as a reinforcement. It has also been reported that the solid polymeric composite wastes are recycled and used in the manufacturing of polymer mortars and concrete structures to be used in the low-cost building infrastructure [80].

Based on the aforementioned discussion, it is clear that even after few cycles of recycling, composites were able to retain most of the properties thereby having potential for their utilisation in a number of applications. The use of these recycled materials in applications will significantly contribute to the sustainability aspect and will also greatly reduce

Table 3
Mechanical properties of recycled biocomposites.

Matrix	Reinforcement	Mechanical properties before recycling	Mechanical properties after recycling	Reference
PLA	Sodium bicarbonate treated sisal fibre	~ 56 MPa tensile strength ~ 101 MPa flexural strength	~ 22 MPa tensile strength after 8 cycles ~ 29 MPa flexural strength	[69]
Epoxidised natural rubber	Carboxymethyl chitosan	~ 2.6 MPa	~ 1.5 MPa after 3 cycles	[75]
Epoxidised natural rubber	Citric acid modified bentonite clay	~ 4.2 MPa	~ 3.15 MPa after 3 cycles	[76]
PLA	Enzymatic treated cellulosic fibres (2 wt.%)	–	~ 800 MPa Young's modulus ~ 38 MPa Stress at yield	[77]
PP	Un-carbonised bagasse (20 wt.%) Carbonised bagasse (30 wt.%)	–	9.2 MPa tensile strength 11.34 MPa tensile strength	[78]
High-density polyethylene /poly (ethylene terephthalate)	Untreated rice husk (70 wt.%)	–	~ 23 MPa tensile strength ~ 45 MPa flexural strength	[79]
	Alkaline treated rice husk (70 wt.%)		~ 20 MPa tensile strength ~ 35 MPa flexural strength	

the impact on the environment. The circular economic aspect of biocomposites leads to the creation of an environment that is free of polymer waste due to the effective recycling of polymeric materials and wastes. The normal polymeric waste disposal systems that include incineration and dumping in landfills lead to a negative effect on the environment because incineration causes harmful greenhouse gases whereas landfills require a huge amount of space and can leach toxic substances into the groundwater. However, by recycling of polymeric composite materials, the above-mentioned disadvantages can be avoided and can effectively manage waste disposal and will contribute significantly to CE where the end life of a material is extended and waste is used to generate composite with acceptable performance properties. In general, it can be conclusively stated that research and development on the recycling of completely bio-based polymeric composites are still only at a preliminary stage and hence a deep understanding on the different factors that affect the properties, economy and sustainability aspects is the need of the moment.

4. Environmental impacts

The use of bioplastics and biofillers creates an initial advantage for the adoption of the CE model because the composites developed can be easily recycled and/or decomposed without leaving any harmful residues. For example, because of the presence of organic composition, PLA can easily be biodegraded through microorganisms that can feed on it [85]. Furthermore, compared to other plastics, burning or landfilling of PLA does not produce high amount of toxic emissions and leachates and it is reported that PLA uses 30–50 % less fossil fuel, leading to a 50–70 % reduction in CO$_2$ emission compared to oil-based plastics [86]. In another study, Madival et al. [87] reported lower CO$_2$ emissions from PLA materials when compared to PET. In addition, it has been reported that the GHG emission of PLA may vary depending on the type of blending material, the reinforcement and the system boundary. Blending of bioplastics (to other synthetic plastics) could lead to the modification of properties (including biodegradability, mechanical and thermal properties) that allow the tailoring of the characteristics for a desired application [88].

Thermoplastic starch (TPS) is another bioplastic that is rigid, biocompatible and biodegradable [89]. TPS is degradable in both soil and water and can be used as compost. However, TPS has poor mechanical strength and it is hydrophobic [90]. Consequently, TPS is only used in limited applications having low moisture content and short life span, such as packaging applications. TPS can be blended with other plastics. In this regard, Mahalle et al. [91] manufactured wood/PLA composite blended with TPS (30% wood fibre+35% PLA+35% TPS). The results of LCA showed better performance of the TPS blended composite in terms of global warming and O$_3$ depletion. The TPS composite blend showed reduced O$_3$ depletion (1.04E^{-07} kg CFC-11) compared to the PLA/wood composite (1.70E^{-07} kg CFC-11) and absolute results of PP (2.20E^{-07} kg CFC-11). Increased O$_3$ depletion in PLA composite was due to the upstream production of PLA, which consumed more input energy. For lower O$_3$ depletion in TPS blended composite, the contribution of wood was <1 % and for TPS, it was 18.05%. This investigation shows that the blending of the TPS with other bioplastics could lead to an increase in its environmental performance. Suwanmanee et al. [92] also reported the environmental performance of PLA blended starch material by comparing the results with that of PS and PLA. It was reported that the PLA/starch material contributed to 73–97 % of total absolute score in affecting the global warming potential (GWP) factor, which is due to the incorporation of indirect land-use change emissions.

PHAs are bioplastics that are biodegradable and recyclable [93], consisting of polyesters of R-hydroxyalcanoic acid [94]. Qiang et al. [95] used polyhydroxyalcanoates (PHA) blend in PLA wood composites. The authors produced two different PLA composites, namely PLA wood composite (20 wt.% wood fibre + 80 wt.% PLA) and PLA wood composites blended with PHA (20 wt.% wood fibre + 55 wt.% PLA + 25 wt.% PHA). The CO$_2$ emission from the PHA blended composite was 3591 kg CO$_2$ eq./t, whereas the same for the PLA composite was 3742 kg CO$_2$ eq./t. Overall, the environmental impact of PHA blended composite (1.9 points) was somewhat lower than that of the PLA composite (1.6 points). This investigation revealed that the sustainability of PLA-based composite can be enhanced by integrating PHA, however, the authors used the cradle-to-gate approach for the LCA assessment, which does not include the product utilisation and the end-of-life phases.

The cost of bioplastic production is high, which can be controlled by the partial use of natural biomass materials as a reinforcement. Natural fibre reinforcement in bioplastics minimises production costs and increases the strength of bioplastics while simultaneously reducing GHG emissions and carbon footprint. As reported, the carbon footprint of natural fibres is about 80 % lower than that of synthetic carbon and glass fibres [96]. For example, the total carbon footprint calculated for the production of one tonne of glass fibre is 1.7–2.5 tonnes of CO$_2$-eq and 0.3–0.5 tonnes of CO$_2$-eq for natural fibre [96]. Singh et al. [97] calculated the carbon footprint of four different natural fibres, i.e. jute, kenaf, flax and hemp. The carbon footprint of these bast fibres was between 400 and 600 kg of CO$_2$-eq/t. It also reported that their carbon footprint was 20–50% lower than synthetic fibre. Broeren et al. [98] studied the GHG emission of sisal fibre and compared to glass fibres. The sisal fibre had a lower GHG emission of 75–90 %. These outstanding GHG emission results of natural fibres indicate that they are sustainable and are a viable reinforcement material for bioplastics.

In addition to these materials, bio-waste has also been used as a filler for the development of environmentally friendly biocomposites. Agricultural wastes such as rice husk and wood flour were used as fillers for the development of polybutylene succinate composites [99]. Biodegradability of the composites was tested through a soil burial test. The composites showed a weight loss of 5 to 10% over 120 days of burial. The weight loss was found to be linear from the initial date of burial confirming the biodegradability of the rice husk and wood flour based biocomposites. Elsewhere, Ambone et al. [100] used waste leather buff (WLB) as a reinforcement for the development of PLA composites. It was reported that the use of leather waste in PLA composite is an alternative solution for the management of leather waste since it reduces the incineration of leather waste. In this research, the composite showed improved tensile strength (45 MPa–10 wt.% WLB) compared to the virgin PLA. Biochar has been identified as a potential filler for the manufacturing of composite materials in the recent years [101]. Biochar is produced by the pyrolysis of biomass at a low or zero oxygen content. Transforming biomass into biochar is an efficient way to control GHG emissions by preventing the decay of biomass [102]. Tadele et al. [103] produced biochar from Miscanthus plants and reported a GWP of 117.6 kg of CO_2 eq/t throughout its life cycle. The highest GWP of 23.3 kg CO_2 eq/t was recorded during cultivation and the lowest was attained during transportation (4.8 kg CO_2 eq/t). Tadele et al. [104] further investigated the environmental impacts of biochar and PP composites. In their work, two PP composites were manufactured with 30 wt.% biochar and 30 wt.% talc reinforcement. The biochar added composite showed a 25% lower environmental impact than the talc reinforced composite. The matrix/filler ratio has been reported to be the major contributor to the environmental impact of PP/biochar composite. This led to the conclusion that further reductions in the environmental impact can be achieved by optimising the matrix/filler ratio.

4.1. LCA assessment on biocomposites

LCA is a technique used to analyse the impact of the individual stages of a products lifespan (from the manufacturing of raw materials to disposal) on the environment [105]. The protocols for LCA implementation are documented in ISO 14040 – ISO 14044 series [106,107]. LCA could be used to test products in the CE models to reveal the limitations and the effect on factors such as global warming, acidification, water use, energy, climate change, etc. so as to establish measures for continuous improvements [108]. LCA studies have three main approaches, cradle-to-factory gate, cradle-to-cradle and cradle-to-grave [109]. In the cradle-to-factory (C2F) approach, the life of a product is assessed partially, i.e. from extraction to the factory gate, but in the cradle-to-grave (C2G) approach, the entire life of the product is analysed from extraction to disposal [110,111]. The cradle-to-cradle (C2C) approach also assesses the entire life of the product, however, the product should be truly or naturally recyclable (i.e. biodegradable) [112]. Of these approaches, C2G and C2C are popularly used in the LCA of biocomposites [111]. These LCA methodologies has been extensively applied for the estimation of GHG and carbon footprint of biocomposites. This section reviews the research on LCA assessments of biocomposites.

Ita-Nagy et al. [113] conducted LCA of bagasse fibre reinforced biocomposites and compared them with 100% sugarcane bioPE and fossil-based PE. According to their analysis, the biocomposites outperformed the 100% sugarcane bioPE in global warming, O_3 formation, terrestrial acidification and fossil resource scarcity. However, an improvement was seen in just global warming and fossil resource scarcity in the comparison of the biocomposites with fossil-based PE. It was concluded in the study that, although bagasse fibre reinforcements minimised the environmental impacts of the original materials, further property enhancement is required to facilitate its use as a replacement for fossil-based PE.

It is worth mentioning that, most of the LCA assessments of biocomposites and plastics focus on the End-of-Life (EoL) assessment, which allow the assessment of landfilling, recycling and incineration. Beigbeder et al. [114] reported that the EoL of biocomposites should be accessed prior to their production and commercial installation to reduce their environmental impact throughout their life cycle. EoL results of biocomposites could facilitate material selection during product development. Beigbeder et al. [114] investigated the EoL of two biocomposites (wood flour/PP and flax fibre/PLA composites) through LCA assessment. The EoL investigation was conducted in four areas, namely, incineration, landfilling, composting and recycling. Both composites had reduced environmental impacts when they were recycled. However, biocomposites are incinerated due to a lack of recycling directives and a composite market for recycled biocomposites [115]. It should also be noted that the separation of the reinforcement from the biocomposite matrix is challenging. For example, a thermoplastic matrix is heated to the crystalline melting point during the manufacturing of organic wood-based composites [116]. In the molten state, wood particles are added to the matrix to develop a strong irreversible bond. The strong interaction between wood and thermoplastic matrix makes recycling difficult, however, it is possible to recycle thermoplastics without reinforcement [116]. Recycled thermoplastics have lower environmental effects than virgin plastics [117]. Bolin and Smith [118] compared the LCA of wood-based composites and alkaline copper quaternary treated lumber used for decking applications. Wood-based composites were developed with 25 wt.% of HDPE, 25 wt.% of recycled HDPE and 50 wt.% of recycled wood flour. Compared to wood-based composites, treated lumber showed 3 times lower GHG emissions and 14 times lower fossil fuel use. Importantly, the authors noted a significant reduction in the LCA results of recycled HDPE when compared with virgin HDPE. The use of 100% recycled HDPE in wood composite fabrication reduced the utilisation of fossil fuels (i.e. 4.4 times the value of treated lumber) when compared with virgin HDPE made wood composite (14 times the value of treated lumber). It was concluded that the composites based on recycled wood are environmentally friendlier than the virgin HDPE.

In the area of biocomposites, numerous investigations have been conducted on the LCA of natural fibre composites to understand their environmental aspects and impact [119,120]. Natural fibre composites use renewable reinforcements that could reduce environmental impacts, but it is essential to understand the process of extraction of fibres, chemical treatment, transport during production, and composite production in order to carry out a thorough environmental impact assessment [120]. LCA results from natural fibre composites showed that natural fibre composites have reduced dependence on non-renewable energy/materials, reduced GHG emissions, increased energy recovery, minimised pollution and EoL biodegradability of components [28,121,122]. Natural fibres in polymer composite manufacturing could reduce the consumption of fossil fuels. It has been reported that a 50% replacement of glass fibre composites in North American auto applications with natural fibre composites could lead to a reduction in CO_2 emissions of up to 3.07 million tonnes, saving 1.19 million m^3 of crude oil [123]. Natural fibre-based composites play a critical role in the storage of carbon since they control the emission of carbon from natural fibres by reducing decay and burning of natural fibre [123]. However, this can only be achieved for a limited period, i.e. until the disposal of the composite material, and it cannot be adapted in all countries because of the application of varying disposal methods. [124].

De Vegt and Haije [125] compared LCA of flax fibre epoxy composite with glass fibre polyester composite and epoxy carbon fibre composite. Flax fibre composites showed better LCA points (1.85) compared to glass and carbon fibre composites (2.4). In another study, Schmehl et al. [126] carried out LCA of hemp fibre and glass fibre based triglycerides and polycarbonic acid anhydride composites used in the manufacturing of bus body components. The composite LCA was analysed employing three factors, namely human health, ecosystem quality and resources. Hemp fibre composite had the lowest LCA value of 0.36, which was 50% lower than glass fibre composite (0.74). These two investigations demonstrated a better LCA of natural fibre composites against synthetic fibre composites. It was observed that the optimised material input was critical for natural fibre composites, and investigation with a varying natural fibre reinforcing percentages could result in variations in the LCA output. It is anticipated that optimised reinforcement of natural fibre could lead to a reduction in environmental impacts.

The use of natural fibre composites in the automotive industry helps to control global warming, as the use of natural fibre mitigates the process energy and aids in carbon sequestration [127]. It has been reported that automobiles contributed 28 % of total GHG emission in the United States in 2018 [128]. This can be improved by controlled fuel utilisation and emissions. The use of hemp fibre/epoxy composite in the automotive side panel reduced manufacturing energy by 55 % compared to the production of neat acrylonitrile butadiene styrene (ABS) doors [129]. Furthermore, the hemp fibre reinforced composite side panel showed a reduced weight of 27 % compared to the neat ABS made composite side panel, which contributed to an 80 % reduction in fuel consumption during the use phase. Shen and Patel [130] recommended natural fibre-based composites for automotive parts manufacturing, such as front sub-frames and interior side panels, due to a 15 % reduction in GHG emissions compared to traditional materials. Similar to synthetic fibre composites, natural fibre composites have comparable LCA results in the production phase. Better LCA can be noted for natural fibre composites only when the utilisation and disposal phase are considered [131]. On this basis, it can be concluded that the production phase of natural fibre composites is a crucial stage in environmental impact assessment. However, the production phase and EoI of natural fibre composites have not yet been clearly addressed, which need to be investigated in order to ascertain their effect in the LCA. For instance, in the investigation done by Luz et al. [132] it was reported that sugarcane fibre reinforced PP composite had 25 % reduced emission than talc reinforced PP composite during the production and recycling phase. In contrast, Alves et al. [133] reported that in the production phase jute fibre polyester composite had 8% higher environmental impact than the glass fibre polyester composite. The environmental impact reported on LCA on biocomposites is shown in Table 4.

In summary, the introduction of the LCA in CE model could increase the chances of mitigation of environmental impacts, which would also allow CE decision-makers to assess the environmental impacts of trade-offs. In addition, in the CE of biocomposites and recycled biocomposites, LCA can show a clearer picture of their impacts. In the recycling and reuse of bio-composites, LCA could facilitate the process of recycling that provides valuable recycling at industrial scales. In order to achieve this, it is essential to develop appropriate manufacturing technology, without which the benefits of CE and LCA cannot be attained.

5. Economic impact of biocomposites

The current study has shown that compared to conventional polymeric materials, biocomposites have comparatively lower environmental impacts. However, the sustained production and application of biocomposites on a commercial basis is highly dependent on the cost involved [140]. Biocomposite fabrication using natural fibres have been presented as a viable option for reducing the production cost. Rodriguez et al. [136] applied a life cycle cost performance method to assess the economic impacts of biocomposites from banana fibre. In their analysis, the production cost was grouped into material, energy, labour and machine costs. Although, the cost of the banana fibre was low, the pretreatments administered for property improvement increased the material cost. However, the authors observed that the manufacturing cost of the banana fibre biocomposite was 17 % less than that of the polyester resin. Additionally, substituting fibre-glass with natural fibres reduced the production energy cost by 80% and the biocomposite cost by 5% [141]. A market research on the global biocomposite utilisation showed an estimate of $19.6 billion in 2020 with an anticipated growth to about $38.07 billion and a compound annual growth rate (CAGR) of 14.2% in 2025. However, the global synthetic fibre market, which was valued at $147.16 billion in 2019 is only expected to grow at a 5% CAGR by 2025 signifying a decrease in the consumption rate [53]. In addition, global plant fibre production has increased exponentially over the last 20 years and is expected to grow from 107 million tonnes in 2018 to 145 million tonnes by 2030 [142]. With increased technological innovations geared towards identifying novel composite materials and new applications coupled with investment in research and commercialisation of finished products, the biocomposite market size will grow considerably resulting in a further increase in the economic benefits of biocomposites [143].

6. Introduction of CE in biocomposite manufacturing: opportunities and challenges

The adherence to the CE improves material diversity and optimises energy use, resource as well as recycling efficiencies. Composite waste, like all other materials in the waste stream, needs to be recycled and looped into production in order to fit into the CE model [144]. However, the processing methods must meet environmental standards, government legislations, acceptable energy usage levels for recycling and cost [145–147]. There is a myriad of challenges in relation to the integration of composites in CE (mostly related to the recycling aspect) that have been reported in the literature. This section reviews these challenges and presents possible measures for addressing them. Fig. 7 shows the CE concept for the fabrication of bio-based polymeric composites.

There have been some studies regarding recycling of composites wastes to make new composites. Nevertheless, the inability of consumers, product manufacturers and policymakers to appreciate the recycling value of composite waste has limited its research to lab-scale investigations. It is worth stating that, most of the regulations and legislation governing the processing of composite waste consider them as plastic waste. Therefore, there exists a lack of implementation of suitable waste management techniques for composites [149]. This has also translated into extended procedures for certifying new methods of recycling and reuse as well as products made from composite waste [71]. Due to the complexity of the composition and/or constituents of composite waste, it is required that policymakers consider composite waste as a separate component of the waste stream to enforce stringent measures for its management. Documentation of material handling from the raw state to end-of-life can be a crucial step in achieving an effective CE.

In the work of Yang et al. [71], the authors found out that the lack of efficient and well-organised collection and transportation systems for the delivery of composite waste limit the effectiveness of the CE system. Although much efforts have been invested in achieving a coordinated collection process, the rates are rather low. The means of transportation of composite waste is also highly dependent on the size of the material. In light of this, it is much more convenient to transport lighter and smaller scraps than products like discarded vehicles or aircraft, which must be disassembled before transportation.

The dismantling and separation of bio-based fibres from the polymer matrix is yet another pertinent issue encountered in the circularity of composite waste. The combination of materials with different chemical compositions in conjunction with the various manufacturing processes the product undergoes makes it almost impossible to separate the constituents of composite waste without damaging the fibres [150,151]. ‘Simpler’ products can be manufactured by reducing the types of materials in the design stage of the product while maintaining quality. Alternatively, the use of additives that enhance the separation and recyclability of composites can be encouraged. The research on recycling of composite waste has been an area of progressive interest for over the past two decades. The development of new technologies for fibre retrieval and recycling involves huge investments in terms of time and money. However, one major problem faced by the research institutions and industries is that most materials get out-of-date before their recycling technologies mature for industrial applications [71,152]. Hence, these industries fail to meet the bulk material demand required to commercialise the technologies. Technology development could be geared towards a more generalised approach suitable for processing materials with a wide range of properties.

Table 4
LCA results of biocomposites (Environmental impact).

Biocomposite manufactured		Material used (product/biocomposite)	LCA approach used	System boundaries	Findings	Reference
Matrix	Reinforcement					
PP	Biocarbon and Miscanthus fibre	Biocomposite made automotive component	Cradle-to-grave	Resource extraction, transportation among life cycle stages, processing and conversion, manufacturing, use of the products, and disposal.	Fabricated biocomposites showed lowest GWP of 11.08 kg CO_2 eq. for conventional material it was 12.53 kg CO_2 eq.	[134]
PLA	Chicken feathers	Biocomposite	Cradle-to-gate	Chicken feathers stabilisation, crushing and composite plate manufacturing.	Addition of chicken feather to PLA reduced the environmental impact, PLA/chicken feather composite showed GWP of 4.10E+01 kg CO_2 eq.	[135]
Polyester	Banana fibre	Biocomposite	Cradle-to-manufacture	Banana fibre conditioning (cut, extraction, washing, and drying) and biocomposite materials manufacturing (pretreatment of BF and biocomposite materials fabrication).	The major contributor to the environmental impact was polyester (63.3 %), while the impact of banana fibre was 36.7 %.	[136]
PLA/TPS	Wood fibre	Biocomposite	Cradle-to-gate	Raw material extraction, input manufacturing, pre-treatment of inputs and biocomposite manufacturing.	TPS causes less environmental burden than PLA. PLA environmental performance increased when it was blended with TPS	[91]
PLA	Dried distillers grains with solubles, flax, hemp, rice husks, wood, glass and talc	Biocomposite	Cradle-to-grave	Raw material acquisition, transportation, manufacturing and processing, consumption, and end-of-life treatment.	Compared to organic filler talc and glass, organic filled reinforcement in PLA showed reduced environmental impact, and energy intensity.	[137]
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)	Vine shoots	Biocomposite made rigid trays	Cradle-to-grave	Vine shoots collection, transportation, tray manufacturing, use, and end-of-life treatment.	20 % of global warming was reduced by the addition 30 vol.% of the vine shoots to the virgin PHBV.	[138]
Melamine	Empty fruit bunch (EFB)	Biocomposite made tableware	Cradle to grave	Palm fibre preparation, melamine compound preparation, tableware manufacturing, use and disposal.	Increase in the EFB reinforcement reduced the climatic change. 30 wt.% of EFB reinforcement reduced the climatic change by 21 % and for 10 wt.% EFB reinforcement it was 1.4 %	[139]
PP	Sugarcane bagasse/talc	Biocomposite	Cradle-to-grave	Raw material production, composite manufacturing and processing, use, and end-of-life treatment.	During production and recycle phase talc/PP composites showed 25 % high emission than the sugar cane bagasse/composite	[132]

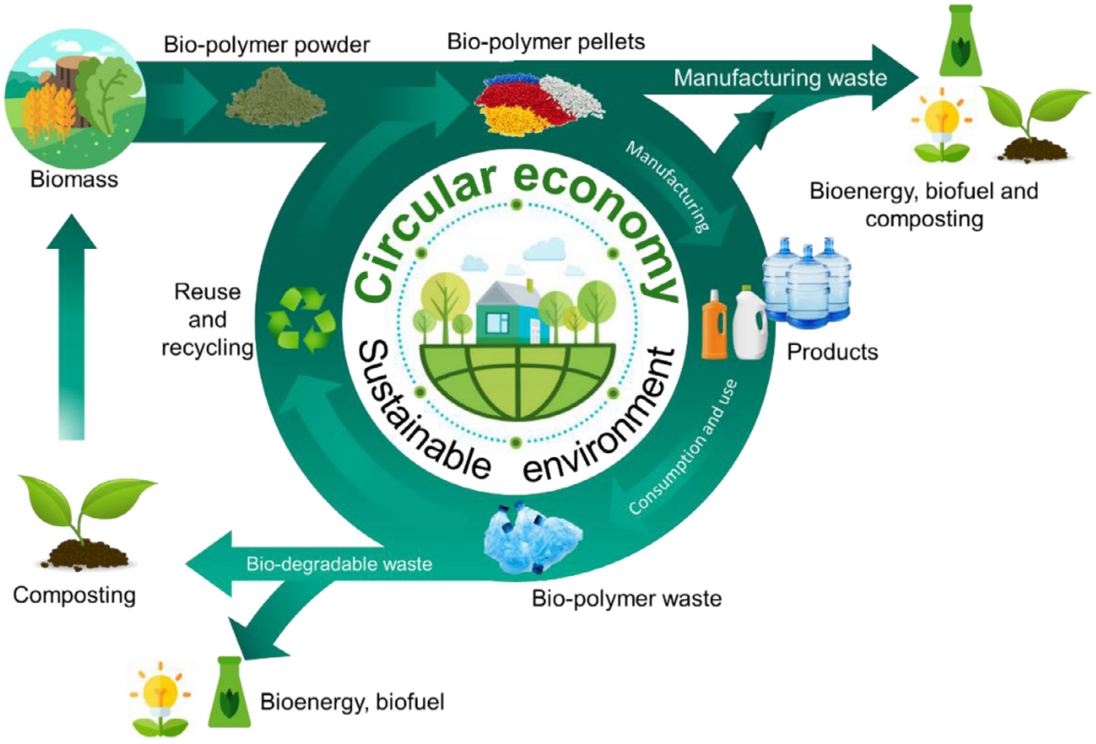

Fig. 7. CE for bio-polymeric composites manufacturing. Figure drawn based on data from Ref. [58,148].

Gopalraj et al. [153] conducted an in-depth review on the life cycle of composite waste and their recyclability. In their analysis, it was stated emphatically that, although the replacement of virgin composites with recycled materials is promising, the environmental effects are inversely proportional to the profit margins made by the recycling industries. Recycling processes can present high energy, carbon footprints and contribute to the release of toxic chemicals. Lee at al. [154] reported the average greenhouse gas emissions for chemical recycling of composites to be 1196.22 g CO_2-eq and 5916.08 g CO_2-eq for the pyrolysis process. The impact of composite recycling on climate change was also evaluated by Witik et al. [155]. Even though lower impacts were observed for recycling as compared with incineration and landfilling, recycling stood a 20% chance of negatively affecting the climate zones.

The increase in energy requirement and high processing cost of fibre recovery in composite waste management result in an increase in the prices of recycled materials usually even higher than the price of virgin materials [156]. The assessment from Roux et al. [157] proved that recycling cost is dependent on the complexity of the material. The cost factor tremendously decreases the demand for recycled composite materials as consumers opt for relatively cheap and quality virgin materials [158]. Technological advancement in efficient recycling methods and material development within the acceptable energy levels, quality and cost will drastically support the implementation of CE [159]. Lower cost of the recycled composite will increase its applicability, market demand and in turn, minimise the dependence on raw materials.

Lastly, some separation and purification techniques, as well as recycling treatments such as acid treatments and thermal recycling methods, reduce the mechanical properties like the tensile strength of the recycled composites. Pyrolysed composite waste retains just about 70–75 % of its strength. This reduction in strength further minimises the overall performance of the recycled material in subsequent applications. To increase the quality of recycled composites, manufacturers combine them with virgin materials to compensate for the reduced mechanical properties. Furthermore, technologies such as gamma irradiation are being considered as an alternative to the conventional recycling methods since it greatly improves the physicochemical and mechanical properties of composite waste [160]. Other developed techniques such as tape and hybrid yarn spinning technologies give the materials excellent tensile properties [161]. The fish bone diagram in Fig. 8 summarises some strategies which can be implemented to enhance the recyclability of composites without compromising on their performance properties.

7. Benefits of circular economy in biocomposites

CE in biocomposites manufacturing benefits the environment, economy and society (Fig. 9). A high amount of energy and a relatively high unit cost per kilogram of weight is associated with compositeshence, their disposal or dumping in landfills represents a loss in high-value materials and economy and eliminates any chance of re-using these high-value materials. Therefore, the need of the hour is to develop business opportunities for recycling of these materials through a CE model [162]. Methods or processes to improve the recyclability of fibre reinforced composites (FRCs) is an important factor in economic benefits for both the user and the producer. The major advantage of these recycling processes will be the recovery of high energy materials, which presents a pathway towards lower energy consumption and economic profit while the reduction in impact on the environment is the added advantage. All these factors are driving the interest in improved recycling processes for composite materials. The recovered matrix (thermoset or thermoplastic) and the reinforcement (fibre, particulate, etc.) can be either mixed again together or used separately for different applications. Hence, the current major aim of the composite industry and research is to achieve reliable recycling processes that can be used to recover materials from both scrap and end of life composites.

The productivity and sustainability in the CE can be enhanced by the effective recycling of biocomposites. In fact, a CE approach in the case of fully bio-based composites can provide suitable incentives for the effective recycling and re-use of both the polymeric matrix and the reinforcement. This approach is highly significant to society because polymeric wastes are a severe threat to the environment thereby making a suitable and practical end of life treatment for these biocomposites a necessity. Recent years have witnessed researchers increasingly focus-

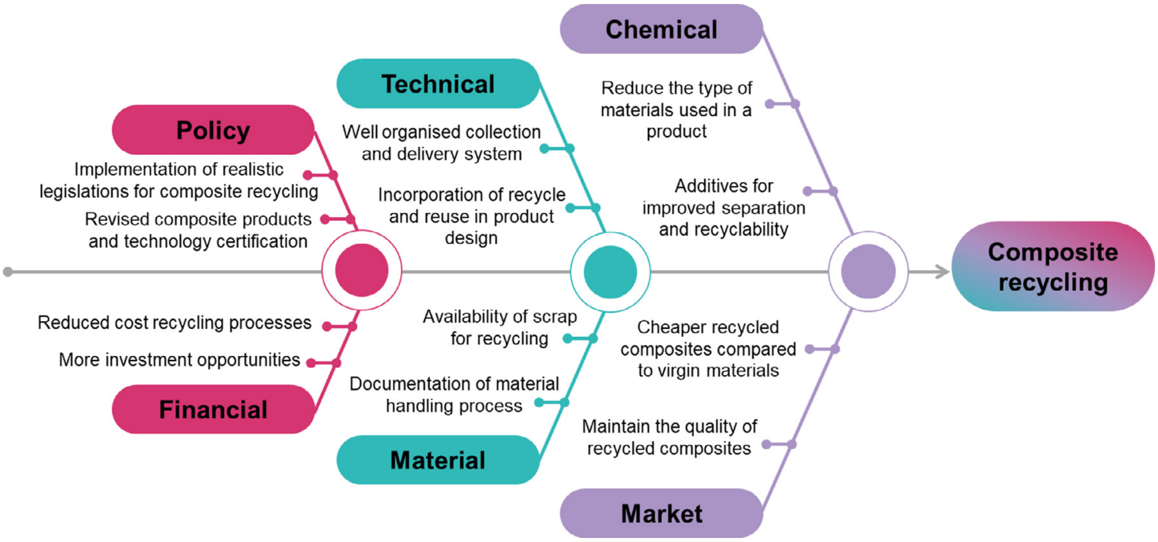

Fig. 8. Strategies to overcome composite recycling problems.

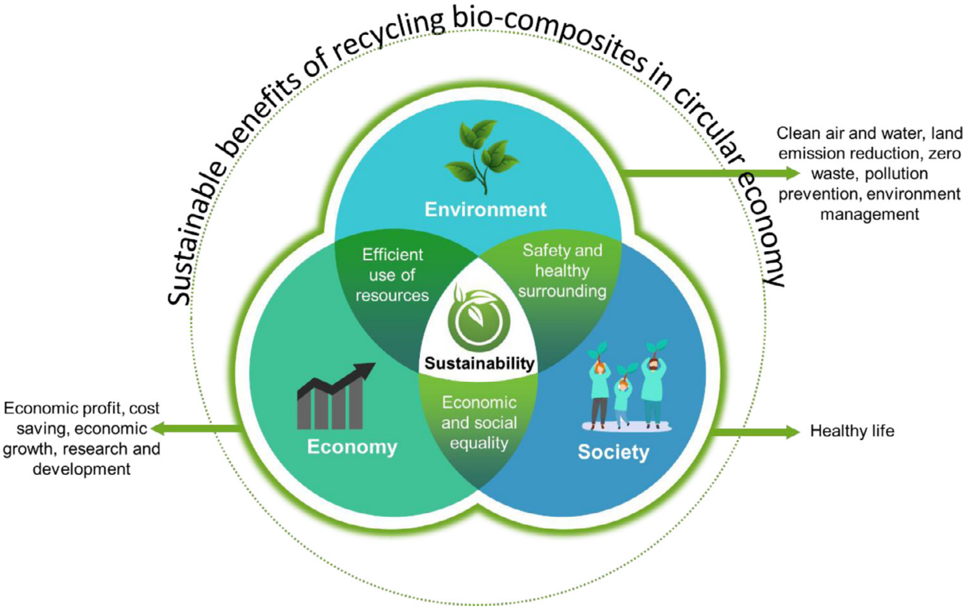

Figure 9. Sustainable benefits of recycling bio-composites in CE.

ing on the area of sustainable designing of composites so as to facilitate the circular economic aspects of composite materials [163]. The major components of this kind of methodology are: a) material life cycle extension and b) recovery of the constituent materials completely after its life cycle by means of recovery processes that ensure the materials stability during this recovery process [56]. As per European commission 2015, the end value of the materials is retained as long as possible and waste is kept at the lowest possible limit in a perfect circular economic scenario [164].

8. Conclusions

This article examines the challenges and opportunities for the development and implementation of the concept of CE in biocomposites. Bio-based polymeric composites have been found to be capable of being recycled, which facilitates the achievement of the benefits of CE. It was realised in this study that although the implementation of CE presents major economic and lower environmental impacts compared to the synthetic counterparts, the assessment of the end-of-life performance of biocomposites has not been significantly explored. In addition, the recycling methods applied for the recovery and reuse of biocomposite constituents are very limited. Consequently, this can minimise the production and applications of biocomposites. To embrace CE in biocomposites, robust technological advancement in relation to material recovery and recycling must be achieved through research and optimisation of the existing methods. Subsequently, innovative methodologies for the planning and development of business models for the CE and product-service solutions should be established. In addition, to further enhance the effectiveness of CE, biocomposite development should also embrace blue economy, that encourages the utilisation of ocean-based resources in creating high-value products. In essence, blue economy points towards the vast untapped resource pool, which when utilised will bolster the concept of CE in biocomposite development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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