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Advancements in biochar-reinforced 3D printing filaments for material extrusion: A review on material performance, sustainability, and circular economy

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Abstract

Additive manufacturing has emerged as a promising technology in the manufacturing sector. However, challenges in achieving the desired thermal and mechanical performance often result in reliance on fossil-based fillers. Biochar, a carbon-rich material derived from agricultural waste, has gained attention as an eco-friendly additive. Factors influencing the performance of biochar-reinforced polymer composite from conventional manufacturing were obtained and investigated in biochar-reinforced 3D printing filaments. With a relatively new research area, this review synthesizes recent progress and pioneering studies on applying lignocellulosic biochar for 3D printing filament for material extrusion. The parameters identified include biochar feedstock type, production method, loading level, and compatibilizers. Biochar produced at lower temperatures (<500.0 ºC) enhances mechanical strength, while higher

temperatures (>700.0 ºC) improve thermal resistance. Successful biochar loading for 3D printing filament ranges from 0.1–0.6 wt% for fruit by-products biochar and up to 50 wt% for wood-derived biochar, with tensile strength, flexural strength, and modulus improved by up to 60.0%, 82% and 175%, respectively. Biochar also enhances interfacial bonding with a compatibilizer, with successful biochar loading increased from 0.6 wt% to 1.0 wt%. This review also explores the broader role of biochar-reinforced 3D printing filaments in advancing a circular and carbon-neutral economy, addressing the 6 "R"s of sustainability, alongside economic considerations, including cost-effectiveness and market potential. The discussion highlights the commercial viability of biochar as a filler and its potential to support sustainable, low-impact manufacturing, positioning it as a valuable solution in the transition toward greener production systems.

***Keywords*:** Biochar; circular bioeconomy; carbon neutral; composite material; 3D printing; polymer.

1. Introduction

The concepts of circular economy, carbon neutrality, and net-zero emissions are widely discussed across various fields, including energy, economic models, sustainability, transportation, integrated technologies, and manufacturing. The circular economy reduces waste by extending product lifecycles through reuse, repair, and recycling, minimizing reliance on new resources [1]. This approach reduces environmental impacts while driving innovation and promoting resource efficiency. By cutting emissions from production and waste, the circular economy significantly contributes to achieving carbon neutrality through reductions and offsets [2]. Meanwhile, the concept of net-zero emissions balances the greenhouse gases released with those removed, aiming to offset the human impact on the climate [3]. Integrating these concepts could reduce waste by more than 4.5 billion tonnes annually by 2050 [4], and is projected to reduce global carbon emissions by 39% or 22.8 billion tonnes annually [5].

Biochar, a carbon-rich material, plays a crucial role in the circular economy to achieve carbon neutrality and net-zero emissions. Biochar closes the loop within a circular economy framework by converting waste into high-value materials, contributing significantly to waste and greenhouse gas reduction. Moreover, this has been extended to the circular bioeconomy, which focuses on reducing fossil-based consumption and replacing it with renewable and environmentally friendly materials [6]. To further support the circular bioeconomy, a readiness level framework by Holden [7] highlights its role within environmental, economic, and social aspects.

Based on a life cycle assessment, carbon neutrality and negative carbon dioxide emissions of biochar can be achieved using different feedstocks, conversion technologies [8], and production scales [9]. According to various life cycle assessment (LCA) studies, torrefaction, a thermochemical conversion technology, produces the lowest emissions [8, 10]. Key factors influencing its environmental performance include temperature and residence time during the

process [11]. Meanwhile, biogenic carbon or carbon derived from biological sources shows net-zero emissions. As biogenic material decomposes, the carbon released is reabsorbed during the plant's photosynthesis, resulting in a carbon-neutral cycle [3].

Biochar has diverse applications, from environmental remediation, and soil enhancement to its emerging role as a sustainable alternative to conventional carbon-based fillers. Its exceptional thermal stability makes it an excellent additive in polymer materials [12]. With biochar's excellent properties, carbon-rich biochar is a promising alternative to replace high-cost fossil-based fillers for enhanced polymer properties. A bibliometric search using the keywords "biochar", "carbon filler", and "polymer" yielded a total of 202 documents from Science Direct, Scopus, Springer, and Wiley, indicating a strong research interest in biochar-reinforced polymer.

Applying biochar in additive manufacturing (AM), or 3D printing, as a carbon filler supports the transition towards sustainable materials. AM builds an object layer by layer from a computer-aided design (CAD). It also supports composite materials and polymer waste upcycling. In 2020, an estimated 360 million metric tons of polymer waste were generated, projected to double by 2040 [13]. Recycling through AM can reduce marine plastic pollution, which accounts for 80% of ocean debris [14]. This supports circular economy goals by giving waste polymers a new lifecycle [15]. Expanding the applications of polymers and recycled polymer waste through AM requires improving their properties [16]. Nanomaterials and carbon-based fillers like carbon black [17], graphene oxide [18], and carbon nanotubes can enhance structural, thermal, and mechanical performance [19]. However, these fillers are fossil-based, costly, and include sustainability concerns. Graphene oxide costs €100,000/kg while carbon black costs €1.2/kg [20]. Thus, biochar has gained attention as a more sustainable and cheaper carbon-based alternative. Using keywords "biochar" and "additive manufacturing" or "3D printing" identified 370 records. However, not all of these publications addressed the

use of biochar as a reinforcing filament for 3D printing filament specifically for material extrusion (MEX), which is the focus of this review. Therefore, the screening process followed the PRISMA 2020 framework to ensure an unbiased selection, as shown in **Fig. 1.**

1.1. Motivation and focus of the study

While biochar–polymer composites for conventional manufacturing have been extensively studied, their application in 3D printing remains largely unexplored. Using the PRISMA 2020 framework for paper selection, it was observed that the use of biochar derived from lignocellulosic biomass as a filler for 3D printing filaments in MEX is still a relatively new research area, with limited understanding of how biochar characteristics influence the properties of 3D-printing filaments. Currently, no review paper has specifically evaluated biochar derived from lignocellulosic biomass for different 3D printing filaments for MEX. Therefore, understanding its performance serves as the primary motivation of this review.

Meanwhile, the primary focus of this study is to identify the key factors that influence the mechanical and thermal performance of biochar–polymer composites. These factors are further examined in the context of biochar-reinforced 3D printing filaments for MEX. The critical balance between biochar and enhancing the filament performance is needed to support its sustainability. This review emphasizes the analysis of initial breakthroughs and pioneering developments to optimize biochar-reinforced 3D printing filaments. It also identifies suitable biochar loading ranges based on material type and processing conditions, providing recommendations for achieving optimal performance and serving as a foundation for future development of biochar-based 3D printing filaments and processing strategies.

Moreover, this review includes the sustainability potential of biochar as a carbon-negative filler, which enhances the filament's properties and reduces environmental impact.

Furthermore, prior studies have separately examined biochar's role as a polymer filler or its environmental benefits; no existing review systematically links biochar feedstock type,

production parameters, loading levels, and compatibilization strategies to the mechanical and thermal performance of 3D printing filaments. For this reason, this paper's objective are as follows (i) provides analysis of biochar-based polymer composites processed using conventional technologies, focusing on the relationship between biochar sources, production methods, loading rates, and compatibilizers on composite's thermal and mechanical performance (ii) highlights recent advancements in their application for MEX, focusing on recent findings in biochar-reinforced 3D printing filament (iii) investigate how parameters affects the performance of biochar-reinforced 3D printing filament (iv) investigate its economic and commercial feasibility, and its role in circular bieconomy as a sustainable solution for next-generation manufacturing.

This review also addresses a critical literature gap by being the first to comprehensively integrate material science, sustainability, and additive manufacturing perspectives on biochar-reinforced 3D printing filaments. By consolidating these domains, this paper synthesizes scattered findings and positions biochar as a technically viable and environmentally superior alternative to fossil-based fillers for next-generation, sustainable additive manufacturing.

1.2. Scope and structure of the study

This review focuses on analyzing the factors that influence the performance of biochar–polymer and biochar-reinforced 3D printing filaments, including biochar properties, production parameters, loading rates, and compatibilizers. The scope of the study is limited to biochar derived from lignocellulosic biomass and its application in enhancing filament performance for MEX. Other additive manufacturing techniques beyond MEX were not included in the present review. The scope and structure of the study are presented in **Fig. 2**.

2. Biochar in the circular economy and carbon neutrality

The circular economy concept minimizes waste, maximizes resource efficiency, and promotes sustainability. Unlike a linear economy, which follows a "take, make, and dispose"

model, the circular economy aims at a closed resource loop with reduced environmental impacts. It extends the lifespan of materials and products through reuse, remanufacture, and recycling, ensuring resources remain in circulation for as long as possible. Meanwhile, carbon neutrality balances environmental carbon absorption and carbon emissions. It has been a continuous commitment in alignment with the Paris Agreement's Goal of limiting global warming to 1.5 °C by 2100. In many developing countries, decoupling carbon emissions from economic growth remains challenging [21].

2.1. Biochar production techniques

Thermochemical conversion methods such as pyrolysis, hydrothermal carbonization, and torrefaction produce carbon-rich solid products, namely biochar, hydrochar, and torrefied biomass, respectively. Pyrolysis, the most widely utilized technique, breaks down biomass into three valuable by-products: biochar, bio-oil, and synthesis gas, within an oxygen-free environment at temperatures ranging from 350 °C to 900°C. The classification of pyrolysis is based on heating rate, operating temperature, and residence time, resulting in four types: slow, intermediate, flash, and fast pyrolysis.

Slow pyrolysis, also known as conventional carbonization, is primarily used to produce biochar. Its main product is biochar (~35%), while bio-oil (~30%) and synthesis gas (~35%) are the by-products. The operating conditions are as follows: temperature range of 300 °C to 700 °C, a heating rate of 0.1 to 1.0 °C/sec, and a residence time of 5 to 60 min. The slow heating rates and long residence times enable the condensation and polymerization of intermediates, resulting in a maximized biochar yield [22]. Fast pyrolysis operates at 600 °C to 1000 °C, a heating rate of 10 to 200 °C/s, and a residence time of 0.5~10 s. The biochar yield is lower (~25%) compared to slow pyrolysis. Lastly, flash pyrolysis operates at 800~1000 °C, with a heating rate of 1000 °C/s and a residence time of less than 0.5 s, producing the lowest biochar yield (~12%). Meanwhile, the hydrothermal carbonization process heats biomass in water at

temperatures ranging from 180 °C~260 °C under low pressure, typically between 2.0 MPa and 5.0 MPa, to produce hydrochar with water-soluble organic compounds as by-products [23]. Lastly, torrefaction, also called "mild pyrolysis," has gained attention since it consumes less energy than pyrolysis. The torrefied biomass yield is highest at ~80%, with by-products of bio-oil (~15%) and synthesis gas (~5%). Classification is light, mild, and severe torrefaction with temperatures ranging from 200 °C to 235 °C, 235 °C to 275 °C, and 275 °C to 300 °C, respectively, with a residence time of 5 min to 60 min. This process reduces biomass moisture and increases energy density [24].

2.2. Biochar as a carbon capture technology

Biochar, a carbon-rich solid product, exhibits exceptional properties, including a high surface area, porosity, and hydrophobicity. Its potential for diverse industrial applications is gaining increasing attention, particularly in advancing environmental sustainability through a circular economy and carbon neutrality. It acts as a carbon capture technology in two primary ways, as shown in **Fig. 3a**: as biochar for soil amendment and as bioenergy products.

Biochar is produced through conventional and modern thermochemical conversion of various biomass sources, which are discussed in the previous section. It acts as a carbon sink by absorbing carbon dioxide during biomass cultivation. The absorbed carbons are locked in the form of biochar, enhancing its potential for long-term carbon sequestration. The primary drawback of biochar production is the emissions generated during the conversion process. Various technologies for carbon sequestration during biochar production are being explored, including using mineral carbonation or adding additives during the conversion process [2]. Jeswani et al. [25] highlighted that bioenergy production with carbon capture technologies emitted negative life cycle emissions ranging from -603 kg CO_2/t CO_2 from biomass cultivation to -1173 kg CO_2/t CO_2 when biochar was incorporated in soil. Furthermore, applying biochar for soil amendment serves as a long-term carbon reservoir, storing a significant portion of

carbon in a stable form. It enhances soil quality by improving water and nutrient retention, resulting in higher crop yields [26].

2.3. Biochar in the circular economy

The circular economy aims to minimize waste and extend product lifespans. **Fig. 3b** illustrates the circular economy model for biochar production. Various feedstocks used for the production include agricultural residues, municipal solid waste, fruit by-products, and industrial wastes. These materials, typically discarded in landfills or incinerated, can be repurposed into biochar, adding new value and reducing environmental impact. This reduces landfill waste and minimizes the cost of waste disposal [27]. These wastes undergo various conversion technologies to produce carbon-rich solid products and valuable by-products such as bio-oil and synthesis gas. It serves multiple purposes, including biorefinery applications, removal of toxic contaminants, industrial processes, and reinforcement additives. When used as a soil amendment, it is reintegrated into the soil, creating a self-sustaining loop. When utilized for electricity generation and industrial applications, carbon dioxide emissions are absorbed by plants through photosynthesis, creating a closed-loop cycle that reinforces the principles of a circular economy.

2.4. Life cycle assessment

Life cycle assessment (LCA) is an effective tool to evaluate the sustainability of a circular economy by providing a comprehensive analysis throughout a product's life cycle. It quantifies the environmental impact of a product, from raw material production, processing, utilization, recycling, and end-of-use. The graphical illustration is shown in **Fig. 3c**.

Traditionally, biochar is used as a soil enhancer. From a cradle-to-grave approach, the average CO_2 removal capacity of biochar, calculated from existing literature, varies depending on the feedstock. Biochar produced from woody biomass has the highest removal potential at -2,576.0 kg CO_2-eq/t CO_2, followed by biochar from Miscanthus or switchgrass at -1,418.0 kg

CO_2-eq/t CO_2. Forest residue-derived biochar achieves -1,202.0 kg CO_2-eq/t CO_2, while biochar from agricultural residues reaches -849.0 kg CO_2-eq/t CO_2. The lowest removal capacity is observed in biochar derived from sewage sludge at -433.0 kg CO_2-eq/t CO_2 [25]. Furthermore, palm-waste-derived biochar implements -660.0 to -933.0 kg CO_2-eq/t CO_2 while its production shows negative emissions -436.0 to -2,065.0 kg CO_2-eq/t biochar production [28].

In addition, significant environmental benefits of using woody biomass and agricultural residues-derived biochar, including average savings in fossil energy consumption (-29 to -300 kg oil-eq/t CO_2 removed), human toxicity (-1.1 to -60.7 kg dichlorobenzene-eq/t CO_2 removed), and acidification (-1.6 to -22.4 kg SO_4-eq/t CO_2 removed). Moreover, biochar derived from forest residues demonstrates net reductions in acidification, eutrophication, and human toxicity, further supporting its role in sustainable carbon management [25]. Furthermore, using a cradle-to-bioenergy product system boundary, the production of algal biochar, cultivated using an open pond under a large-scale production, has -12.35 CO_2-eq/kg biochar [29], while forest residue-derived biochar has -0.85 tons CO_2-eq/t biochar [30].

3. Biochar-polymer composites processed through molding techniques.

The application of biochar as a filler for polymer has received increasing interest due to the biochar's outstanding thermal stability and high surface area. This section highlights the results of a polymer composite processed through conventional manufacturing, with a process illustration shown in **Fig. 4a**.

The composite's mechanical properties are assessed through tensile strength (TS), flexural strength (FS), and modulus of elasticity. TS indicates the maximum stress a material can withstand before breaking, while FS measures its ability to resist deformation under bending forces. The tensile modulus (TM) evaluates the material's stiffness under tensile load, whereas

the flexural modulus (FM) represents its resistance to bending deformation. The range of mechanical and thermal properties of biochar-polymer composites is influenced by various factors, including biochar production temperature, biochar loading, type of biochar, and the use of a compatibilizer.

3.1. Influence of biochar production temperature

The temperature at which biochar is produced significantly affects the mechanical and thermal properties of the composite polymer. Depending on the chosen thermochemical conversion, production temperature ranges from 200.0 ºC ~ 1000.0 ºC. As observed from collected studies, biochar produced at low temperatures resulted in the composite's higher tensile strength, while higher temperatures enhanced thermal stability.

Bamboo-derived biochar blended with high molecular polyethylene (HMP) produced at lower temperatures of 300.0 ºC and 400.0 ºC, compared to 600.0 ºC and 900.0 ºC, shows enhancement in TS, FS, and FM [28]. This is supported by observations from Li et al. [31], Kumar et al. [32], and Giorcelli et al. [33], which showed TS enhancements of 91.2%, 14.0%, and 63.0%, respectively. These observations were associated with the visualization provided by Ogunsona et al. [34] in **Fig. 5a**, where an oxygen-containing functional group interacts with the polymer to develop good adhesion. Although it was also present with biochar at high temperatures, it contains fewer surface functional groups than biochar at low temperatures due to biomass dehydration and deoxygenation [35]. This supports the result in **Fig. 6a**, where the highest TS was achieved in biochar produced at 500.0 ºC [31].

Furthermore, SEM images also support these observations. Voids and gaps were seen in biochar produced at high temperature (**Fig. 5b**), and the observed cracks appeared on the polymer and not within the biochar-polymer interface [34]. These results indicate that the better binding observed from biochar obtained from a lower temperature (**Fig. 5c**) was attributed to

biochar encapsulation within the polymer matrix, leading to improved interaction and performance.

Meanwhile, biochar obtained at high temperatures showed enhanced thermal stability due to the formation of a carbon-crystalline structure [32]. The TGA result is shown in **Fig. 6b**, where weight loss appears lowest for biochar produced at high temperatures. The thermal properties of biochar-polymer composites are presented in **Table 1**. Polymers degrade at 126 ºC, while biochar's thermal degradation starts at 400 ºC [36]**.** This directly contributes to the enhancement in thermal properties of biochar-infused composites.

3.2. Influence of biochar loading rate

Using the screened dataset, **Fig. 7a–7e** illustrates the relationships between biochar loading, biochar and polymer type, and mechanical enhancement**.** It highlights that biochar loading rates typically range from 0.5 wt% to 70.0 wt%, resulting in TS and FS enhancements of 10.0% to 100.0%, while TM and FM enhancements range from 10.0% to 150.0% (**Fig. 7a**).

In the case of wood-derived biochar, the optimal loading range is shown to be from 5.0 wt% to 35.0 wt% **(Fig. 7b)**. These optimal loadings are observed from the experimental works of the following authors. At 10.0 wt%, Zhang et al. [37] reported a 109.0% increase in TM and improved melting temperature by 5.9%, while Ho et al. [38] observed 34.5% TM enhancement. Increasing the loading to 20.0 wt% resulted in TS and FS enhancement of 93.0% and 29.8%, respectively [39].

The highest loading is achieved at 35.0 wt% using date palm waste (*Phoenix dactylifera*) as a filler, with increased TM, FS, and FM by 154.7%, 14.1%, and 100.6%, respectively [40]. However, a higher biochar loading can cause agglomeration during the composite development. At lower concentration (**Fig. 8a-c**), biochar is fully coated by the polymer matrix, resulting in good interfacial interaction. Lower biochar loading shows better adhesion, facilitating good stress distribution and enhancing mechanical performance. At higher biochar

concentration (**Fig. 8d**), microcracks and holes were observed, which were caused by biochar agglomeration within the polymer matrix [39]. The pores in **Fig. 8f** exhibit no meshing force, leading to the mechanical failure due to the formation of stress concentration points.

By-products of fruits, such as bael fruit shells, cashew nutshells, and citron fruit peels, have successfully blended with polymer; however, they cannot achieve a high loading concentration similar to wood-derived biochar. Reported studies used moderate biochar loadings of 5.0 wt% to 10 wt% (**Fig. 7d)**. Cashew nutshell-derived biochar shows maximum enhancement at 10.0 wt% [41], bael fruit shell biochar at 5.0 wt% [42], and waste-citron peel biochar at 2.0 vol% [43]. Furthermore, agri-industrial waste biomass such as corn stover at 2.0 wt% [44], and rice husk at 5.0 wt% [45], as shown in **Fig. 7c**. These observations are associated with biochar type, and are further discussed in Section 3.3.

The optimal amount of biochar may also vary depending on the polymer matrix. In the case of ultra-high molecular weight polyethylene (UHMWPE), it can facilitate higher biochar loading as high as 70.0 wt% [46]. Strong interfacial bonding and homogeneous dispersion are observed, leading to 91.2% and 161.7% enhancement in TS and TM, respectively [31]. Particle size is also one factor when blending with a polymer [47]. The biochar particle size used is reported to be less than 20 μm [31]. Smaller biochar particle sizes promote uniform dispersion in the polymer matrix and reduce agglomeration, improving composite homogeneity [48].

In terms of thermal stability, since biochar exhibits higher thermal stability than polymer, increasing the biochar loadings enhances thermal stability (**Fig. 6c**). The biochar loading and its effect on mechanical properties are summarized in **Table 2**.

3.3. Influence of biochar feedstock type on polymer performance

As presented in the previous sections, the biochar feedstock type can also affect the overall performance of polymer composites. Biochar derived from wood-based biomass typically has loading levels ranging from 10.0 to 35.0 wt%. Moderate loading levels,

between 5.0 wt% and 10.0 wt%, were seen for fruit by-products, while agri-industrial waste-derived biochar had the lowest, from 2.0 to 5.0 wt%.

Proximate analysis of wood-derived biochar shows higher fixed carbon (FC) and lower ash content than other biochar sources. Bamboo-derived biochar has a high FC content of 85.16 wt% while ash content ranges from 3.08~4.65 wt% [49]. Fruit-derived bichar, such as cashew nutshell, has FC of 57.2~58.62 wt% and 4.44~8.20 wt% ash content [50]. Meanwhile, agri-waste biochar, such as corn stover and rice husk, has lower FC, ranging from 29.81~44.87 wt% [51] and 30.81~60.10 wt% [52], respectively, while ash content ranges from 4.96~25.77 wt% for corn stover biochar [51] and 22.19~32.38 wt% for rice husk biochar [52]. These enhancements in the polymer composite were also associated with FC. Higher FC indicates a more rigid and crystalline structure. The stress transfer between polymer and biochar also improved due to the increased surface area, resulting in enhanced performance [53].

3.4. Influence of compatibilizer on composite performance

Compatibilizers have also been reported to significantly enhance the interfacial bonding between biochar and the polymer matrix by modifying the interfacial properties of the composite [54]. When biochar is used as a carbon-based filler, the presence of a compatibilizer further strengthens the bonding strength of the biochar-polymer composite. Maleic anhydride polypropylene (MAPP) compatibilizer is commonly used for polypropylene matrix [55] and shows enhanced TM by 16.7% [36] and TS by 35.7% [56]. Maleic anhydride grafted polypropylene (MA-g-PP) shows enhancement in polymer's TM, FS, and FM by 83.0%, 40.0% and 57.0%, respectively [57].

While compatibilizers provide significant advantages in tailoring composite development, their use may also increase material costs. Hence, the loading rate must be carefully optimized. Das et al. [56] reported that even a minimal addition of 1.0 wt%

compatibilizer yielded notable improvements in the performance of biochar–PP composites without compromising their properties. Moreover, reducing the compatibilizer content to this level resulted in an 18% reduction in production costs.

4. Biochar-reinforced 3D printing filament for material extrusion

Additive manufacturing (AM), or three-dimensional (3D) printing, is a process in which objects are built layer by layer based on computer-aided design (CAD) models. The widely used method in 3D printing is the material extrusion (MEX). This process facilitates the use of thermoplastic polymers and bioplastics, which are melted in an extruder and deposited layer by layer as the extruder moves simultaneously. Thermoplastic is a polymer substance that softens when heated and solidifies upon cooling.

Thermoplastic filaments used for MEX include polymeric materials such as polylactic acid (PLA) [58], butadiene-styrene copolymers (ABS) [59], polycarbonate (PC) [60], polyethylene terephthalate (PET) [61], high-density polyethylene (HDPE) [62], and polypropylene (PP) [63].

PLA is made from sugarcane or cornstarch, a widely used filament for MEX. It possesses biocompatibility and easy processing and has a lower environmental impact. However, PLA has low mechanical strength, which limits its potential application. Acrylonitrile butadiene styrene (ABS) offers improved toughness and strength compared to PLA but is prone to warp and has a high shrinkage factor [64]. Nylon is a synthetic polymer commonly used in the industry due to its strength, durability, and flexibility, but it is sensitive to moisture [65]. Polycarbonate (PC) offers increased flexural toughness, impact, and heat resistance [66]. Polypropylene (PP) is often used for its versatility and heat resistance, while HDPE is generally more flexible at lower temperatures.

With the continuous demand for sustainable materials, developing new filaments with enhanced mechanical, interfacial, and thermal properties has been explored [67]. These include the use of natural fibers and have been extended to the use of biochar. Biochar that has been studied is derived from by-products of fruits such as betel nutshells [68], coconut shells [69], ground shells [70] and tomato stems [71]. Wood-derived materials from olive tree pruning [72], bamboo [73], and wood chips [74], as well as agri-waste like rice straw [45], were also used. The graphical illustration for the development of biochar-reinforced thermoplastic filament is presented in **Fig. 4b** and filament characterization in **Fig. 4c.** Balancing biochar loading and filament performance is crucial to support its commercial feasibility and sustainability [71]. Reported enhancement in TS, FS, TM, and FM, as shown in **Fig. 9a**, ranges from 20.0~50.0 %, 10.0~60.0 %, and 5.0~60.0 %, respectively. The following section highlights the recent advancements in utilizing biochar for MEX, demonstrating strong potential to improve the properties of PLA and other thermoplastic-based 3D printing filaments.

4.1. Biochar-reinforced biodegradable 3D printing filament

PLA is the most widely used 3D printing filament because it is inexpensive, commercially available, and exhibits minimal warping and shrinkage during printing. In addition, its biodegradable nature enhances compatibility with biochar, making it a suitable matrix material. PLA is also the most frequently reported polymer in developing 3D printing composite filaments.

PLA has been successfully blended with biochar derived from fruit and wood byproducts. However, observations indicate that parameters such as biochar loading and type have varying effects on resulting properties. Therefore, customizing 3D printing PLA filaments for a specific application requires evaluating these factors to ensure the desired performance and material properties. With the application of biochar in 3D printing filament being significantly new, most studies start at a lower loading between 0.1 and 5.0 wt%.

Biochar from by-products of fruit was investigated and showed enhanced mechanical and thermal performance at a lower loading of 0.1 to 0.6 wt% (**Fig. 9b to Fig. 9e)**. Biochar from betel nutshells is incorporated into PLA at 0.025 wt% to 0.20 wt% and shows TS and TM enhancement by 51.1% and 58.2% at 0.1 wt% loading, respectively [68]. Similarly, Mandala et al. [70] reported using ground nutshell biochar at lower loadings of 0.25 wt% to 0.75 wt%, where maximum TS increased by 39.8% at 0.5 wt%. This is supported by Umerah et al. [69], where the successful loading of 0.6 wt% resulted in 81.9% TS enhancement. Biochar addition also led to a higher storage modulus in the glassy region, contributing to improved stiffness as observed for tomato-derived biochar with PLA [71]. In addition to biodegradable PLA, 0.5 wt% loading was also suitable for biodegradable polyhydroxyalkanoate (PHA) [75].

Reported enhancements were directly associated with biochar's high intrinsic mechanical properties. Therefore, uniform dispersion of biochar is crucial during the preparation of the composite. Proper biochar distribution within the polymer matrix enables the formation of a reinforcing network, thereby enhancing structural integrity [57]. With strong mechanical interlocking and adequate distribution, biochar helps resist deformation and facilitates effective load transfer [76]. A visualization is provided in **Fig. 10a** showing how biochar agglomeration led to microcrack formation. The SEM images of 3D printing filaments (**Fig. 10b**) also support these findings. Biochar occupies the voids at lower concentrations and completely blends with the polymer. At higher concentrations, biochar can decrease the polymer's performance. Particle agglomerates and the formation of voids were seen, causing a reduction in mechanical performance [68].

Meanwhile, due to the low concentration of carbon particles in the composite filament, minimal improvement in thermal stability was observed. The maximum degradation temperature reached 365.39 ºC and 365.83 ºC at 0.5 to 0.75 wt%, while the neat PLA's

maximum degradation temperature was 361.49 ºC [69]. This is supported by Arora et al. [68] in **Fig. 10c,** where minimal changes in the curve were observed.

On the contrary, moderate loading up to 20 wt% was used for biochar obtained from wood (**Fig. 9b to Fig. 9e)**. At 2.0 wt% olive tree-derived biochar, improved TS and toughness by 21.1% and 22.6%, respectively, were observed. At 4.0 wt% biochar, enhanced FS, FM, TM, and Charpy impact strength by 14.0%, 8.7%, 25.8%, and 141.6%, respectively, were obtained. At 6.0 wt%, flexural elasticity was enhanced by 11.1%. Beyond 6.0 wt% biochar, morphological analysis shows non-uniform layers, voids, and porosity. Incorporating 8.0 wt% biochar enhanced Vickers hardness by 8.7%, demonstrating potential for applications where high hardness is prioritized [77].

The particle size is another aspect for blending a higher biochar concentration with PLA. The highest successful loading is reported at 20 wt% using wood-derived biochar with a particle size not exceeding 10 μm [74]. TM, TS, FS, and FM enhancement of 40.7%, 42.5%, 55.6%, and 57.7% (**Fig. 9d-e**), respectively, were recorded. However, due to higher concentration, the samples are still prone to brittle cracking, with the appearance of voids at higher SEM magnification. With limited data for 3D printing filament to date using the same biochar for comparison, the observed higher concentration can be compared to a composite processed by injection molding, where wood-derived biochar also shows successful blends up to 35.0 wt%, as discussed in Section 3.2. Through continued optimization with higher biochar concentrations to enhance PLA performance, bio-based filaments such as PLA can be further advanced to support biodegradable yet strong materials for sustainable manufacturing [78].

4.2. Biochar-reinforced polypropylene (PP), high-density polyethylene (HDPE), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG) 3D printing filaments

From the results of biochar blends with PLA, biochar as reinforcement in 3D printing filaments was extended to polypropylene (PP), high-density polyethylene (HDPE), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG).

Using olive tree-derived biochar, PP, HDPE, and ABS filaments shows enhancement in TS, TM, FS, and FM by 28.4%, 24.3%, 19.7%, and 27.4% [72]; 37.8%, 29.5%, 35.6%, and 22.3% [79]; and 24.9%, 25.5%, 21.0%, and 18.9% [80], respectively. These improvements are comparable across the three polymer matrices, suggesting that the reinforcing effect of biochar is consistent regardless of the base polymer. In the case of PETG–biochar composites, TS and FS were enhanced by 17.8% and 15.9% [81], respectively, which are slightly lower than the enhancements observed in PP, HDPE, and ABS.

Similar to PLA-biochar filament, voids and pores were observed beyond 6.0 wt% biochar, resulting in a decrease in mechanical properties [72]. These observations indicate that for olive-tree-derived biochar, optimized loading is at 6.0 wt%. Process adjustments are necessary to accommodate higher biochar loadings [82]. To address this, additives and other blending techniques are recommended for better adhesion and to facilitate better binding [56].

4.3. Biochar-reinforced polyamide (PA) 3D printing filament

The highest reported loading of wood-derived biochar in PLA is 20 wt% [74]. However, recent studies demonstrate that the loading can be increased up to 50 wt%, showing excellent dispersion of wood-derived biochar within the polyamide matrix through *in situ* polymerization. In this process, monomers are directly polymerized in the matrix to form a composite. This approach advances beyond the conventional melt compounding and can accommodate higher biochar loading. A significant increase of 110% in TM and 44% in TS was achieved at the highest biochar loading of 50.0%. Even at higher concentrations,

dispersions are uniform and well-combined within the matrix [83]. A significant increase in thermal stability was observed with a large amount of biochar concentration, which is also consistent with findings from other studies [84].

4.4. Biochar-reinforced PLA with polybutylene adipate-co-terephthalate (PBAT) filament and hybrid fiber filament reinforced with biochar

In addition to other blending techniques, a compatibilizer such as polybutylene adipate-co-terephthalate (PBAT) has been reported to help improve the adhesion between 3D printing PLA and biochar. According to the report by Umerah et al. [69], the highest loading with improved performance using coconut-shell-derived biochar is only 0.6 wt%. With the use of a compatibilizer, this was increased to 1.0 wt% biochar [71].

Adding biochar facilitates better binding between PLA and PBAT (**Fig. 11**). SEM observations in **Fig. 11-a1** reveal phase separation, indicating weak interfacial bonding between PLA and PBAT. In **Fig. 11-a2**, phase separation was no longer visible, highlighting better interfacial interaction between the compatibilizer, PLA, and biochar [71]. At 1.0 wt% biochar, 45.0% TS enhancement and increased melting temperature by 2.0 ºC were observed.

However, similar to observations from other studies, increasing the loading impacts particle agglomeration even with a compatibilizer. At higher loading (10.0 wt%), SEM **(Fig. 11b)** showed fibril structure disappearance, indicating increased brittleness in the composite performance. In contrast to the PLA with wood-derived biochar, where a loading of 20.0 wt% is achieved, the highest loading of coconut-derived biochar is only 1.0 wt%.

Another method to improve the performance of 3D printing filament is by hybridizing it with fiber. Bodaghi et al. [73] used bamboo-derived biochar and hybridized it with flax fiber, a natural fiber used for textile production. At 3.0 wt% biochar, TS was enhanced by 248.0% and FS by 207.0%, the highest enhancement recorded in this study. The SEM microphotograph

shows minimal voids, indicating good impregnation of the composites. In addition, at 3.0 wt% biochar, flammability was reduced by 45.0%.

Using a compatibilizer, hybridization with fiber, varying the biochar loading rate, and biochar-reinforced 3D printing filament show improved performance. By optimizing these key parameters, biodegradable 3D printing filament can be effectively tailored for advanced manufacturing applications. Other compatibilizers that can be explored include maleic anhydride-grafted polypropylene, which was used by Watt et al. [57] for wood-derived biochar.

4.5. Influence of parameters on mechanical properties

The different biochar loadings and their effect on the filament's performance are summarized in **Table 3.** By-product of fruit-derived biochar shows higher TS enhancement ranging from 40.0 % to 80.0 % at minimal loadings (<1 wt%). In comparison, wood-derived biochar at moderate loadings (4.0 wt%) exhibits TS enhancement from 20.0 % to 45.0 % but can be increased up to 50.0 wt% biochar using *in situ* polymerization. Compatibilizers and hybridization with natural fibers further enhance mechanical strength and reduce flammability. SEM analyses confirm uniform carbon distribution and graphitic structures in well-mixed composites. While thermal stability remains mostly unaffected or slightly improved, higher biochar content reduces heat flow due to lower polymer content. These findings highlight biochar's role in fabricating high-performance, sustainable composite filaments but emphasize the need for optimized loading [85], printing conditions [86], and potential surface treatments to ensure uniform performance and structural integrity in 3D-printed applications. Machine learning models can also be utilized for printing conditions to examine the influence of MEX settings [87].

5. Sustainability assessment of biochar-reinforced 3D printing filaments for material extrusion

The adoption of biochar-reinforced 3D printing filaments is driven by their environmental sustainability, economic viability, and commercial feasibility. This chapter highlights the role of biochar in closing the polymer's sustainability loop and the current challenges in terms of its financial feasibility and commercial viability.

5.1. Environmental feasibility of using biochar-reinforced 3D printing filaments

The environmental feasibility of biochar-reinforced 3D printing filaments includes biochar's potential for carbon sequestration, feedstock waste valorization, and polymer-enhanced mechanical properties. As shown in **Fig. 12**, the circularity of biochar-reinforced 3D printing filaments begins with using biodegradable, neat polymers or recycled polymers, which follows the R-strategies of circularity, namely reduce, refuse, recycle, rethink, repurpose, and remanufacture [88].

Unlike the linear economy, products follow a take-make-dispose model where waste materials often end up in landfills. The financial burden of plastic waste management is substantial worldwide. In China**,** plastic waste management costs could reach US$2.6 billion annually [89], while in the United States**,** expenses amount to approximately US$660 million annually [90]. On a global scale, plastic waste management has an average cost of US$32.0 billion and is projected to reach US$44 billion by 2032 [91].

Meanwhile, converting agricultural waste is projected to double by 2050, reaching 4 billion tons globally [92], while China alone produced 800 million tons in 2018 [93]. Singapore generated around 840,000 tons of wood and agricultural waste in 2019. Converting agricultural waste into biochar is a sustainable and cost-effective approach to waste management. Upcycling just 5% of 2-3 tons of waste daily into biochar could save SGD 1,650-4,500 in

annual disposal costs [94]. Therefore, valorizing or "repurposing" agricultural waste into biochar reduces waste management costs and offers a long-term, sustainable solution.

Plastic waste from 3D printing includes printed failed prints, test prints, support structures, and unwanted prototypes. These can be reprocessed to produce new filaments. However, recycled filaments show decreased mechanical performance [95]. Thus, instead of using fossil-based carbon filler to strengthen the recycled filament, "refuse" means replacing it with biochar-derived agricultural waste to enhance its performance [15], prolong the product's lifespan [96], expand its applicability, and promote cleaner production [97]. By converting agricultural residues into biochar and integrating it into a neat polymer or recycled polymer, a sustainable material with enhanced performance is created for various industrial applications, such as automotive, aerospace, biomedical, and construction [98]. With improved properties, materials needed to produce new filaments are "reduced", significantly helping in waste reduction [96] by providing recycled polymer with a new life cycle [15].

In addition to reducing plastic and agricultural waste, using biochar instead of fossil-based carbon fillers also contributes to lower environmental emissions. Approximately 15 million tons of fossil-based carbon fillers are produced annually, emitting 29-79 million metric tons of carbon dioxide yearly [99]. Meanwhile, biochar-derived filler is considered a carbon-negative material. Life cycle assessment results demonstrate that incorporating biochar into 3D printing filaments significantly reduces the environmental burdens. Higher biochar concentrations lead to even greater reductions, attributed to biochar's inherent carbon-negative nature [84]. Incorporating biochar in HDPE significantly lowers the global warming potential compared to its fossil-based counterpart. A carbon neutrality (0 kg CO_2 eq) is achieved with 40% biochar loading for recycled HDPE, 50% for PLA, and 52% for neat HDPE [97].

An LCA analysis of biochar-reinforced polyamide filament shows a 49% reduction in carbon footprint with enhanced mechanical performance. Adding the CO_2 sequestered in

biochar further reduces the carbon footprint by 65%. In addition to carbon footprint, other environmental impacts, such as acidification, eutrophication, specifically terrestrial, marine, and freshwater, as well as land use, also show reduced environmental impacts. The acidification and land use decreased by 49% and 47%, respectively, while marine, freshwater, and terrestrial eutrophication decreased by 50%, 50%, and 49%, respectively [84].

The observed reduction in carbon footprint is associated with biochar's carbon sequestration capability, where carbon dioxide released during the product's life cycle is absorbed during the cultivation phase. Liu et al. [100] showed that biochar could lower CO_2 emissions by 0.1 to 0.3 billion tonnes per year, emphasizing its role in mitigating greenhouse gas emissions. Biochar-derived agricultural waste significantly reduces waste accumulation and landfill usage. By diverting organic waste from landfills, biochar can sequester 12,045.0 tCO_2-eq annually, with an additional 29,300.0 tCO_2-eq annually by mitigating methane emissions from landfill decomposition [101].

At the end of the biochar-reinforced 3D printing filament's lifecycle, it can be shredded and "recycled" or "remanufactured" into new pellets or filaments. Compared to neat PLA-based filament, biochar-reinforced PLA filament exhibits greater strength and a longer lifespan. Meanwhile, during the end-of-life stage, the biochar component continues to contribute to environmental sustainability. Even after disposal, the biochar remains stable and retains its carbon within the filament matrix, preventing its release into the atmosphere and thereby supporting long-term carbon capture [97].

5.2. Economic feasibility of biochar-reinforced 3D printing filaments

Any manufacturing system's key challenge is minimizing production costs while ensuring adequate product performance and sustainability. The economic feasibility of biochar-reinforced 3D printing filament depends on several factors, including production costs, material availability, performance advantages, and market demand. AM is seen as a promising

technology that promotes cleaner production with low energy consumption and waste. Its global market is expected to reach US$23.33 billion by 2026. This is supported by its broad application in automotive, medical, and aerospace [102]. This drives the increased demand for low-cost, high-strength materials. Replacing expensive carbon-based filler with agricultural waste-derived biochar can significantly reduce the material cost. Biochar has a lower density and comparatively low cost than commercially available fillers such as nano-clay, carbon fiber, etc [35]. Through biorefinery, the by-products of bio-oil and synthesis gas can be used for energy applications, which further reduces the cost of biochar [35]. Biochar derived from post-consumer and post-industrial waste costs less than 0.3 USD/kg [103].

Several studies have also investigated biochar production's market cost and annual revenue. According to the 2013 International Biochar Initiative (IBI) survey, biochar ranges from US$80.00 to US$13,480.00 per ton [104]. Recent data from 23 biochar companies indicate an average price of approximately US$2512 per ton [104]. Regarding annual revenue, Wrobel-Tobiszewska et al. [105] reported that forestry-derived biochar reached US$179 annually. Furthermore, when comparing production technologies, slow pyrolysis is more economically profitable, at US$18.30 per ton, compared to biochar from fast pyrolysis at US$8.14 per ton [106].

Implementing carbon taxes and revenue generation for carbon sequestration also remains limited. Establishing a carbon trading system that provides farmers with financial subsidies and incentives for biomass production and biochar utilization as a soil amendment would promote the widespread adoption of biochar, enhancing soil health and carbon sequestration efforts [107]. A cost-benefit analysis, incorporating opportunity costs and trade-offs, is also recommended[108]. However, large-scale production of biochar remains limited. Revenue opportunities, such as carbon credits for sustainable manufacturing, subsidies for biomass-based industries, and tax incentives, can drive increased production of biochar and biochar-

polymer. Moreover, the enhanced properties of 3D printing filament [109] can lead to reduced polymer consumption and lower costs. This will drive greater demand for biochar-reinforced 3D printing filament, making it a more attractive and sustainable alternative in various industries. Waste and disposal costs are also lower since it is easier to recycle, enhancing their long-term economic viability.

5.3. Commercial feasibility of biochar-reinforced 3D printing filaments

The rising demand for sustainable yet high-performance materials is driven by growing concerns over climate change and environmental sustainability, particularly in industrial sectors. Its versatility and broad application encourage large-scale production, leading to economies of scale that lower production costs. This will make it more cost-effective and competitive against fossil-based materials.

Another cost-effective approach to scaling up production is the biorefinery concept. A biorefinery can be designed to process multiple raw materials into various products, thereby achieving carbon neutrality [110]. In addition, a biorefinery consists of multiple conversion technologies that can utilize waste materials aligned with the circular economy framework [111] and convert them into high-value products such as biochar-reinforced 3D printing filaments. Recently, smart biorefineries have been introduced to utilize artificial intelligence to enhance the cost-effectiveness of bioproduct conversion [112]. Furthermore, as industries transition to sustainable solutions, the demand for eco-friendly materials grows, leading to increased investment in research and development. With continued advancements in research, technical performance is improved, ensuring long-term viability for high-demand applications across various industries, ultimately strengthening commercial feasibility and driving market adoption.

6. Conclusions

This review has addressed the potential of biochar as a sustainable filler in polymer composites and 3D printing filament for MEX, aligning with the principles of circular bioeconomy and cleaner production. As the industry transitions towards sustainability, this paper provides practical insights and guidelines on biochar types, production conditions, and loading concentrations to achieve desired mechanical properties by reviewing recent findings, supporting the development of sustainable materials for MEX. Utilizing the PRISMA 2020 framework for unbiased literature screening, it addresses the gap by comprehensively investigating the effect of biochar types, loading rates, production temperature, and compatibilizer on composite and 3D printing filament performance. The main conclusions are summarized below.

1. The critical balance between biochar and enhancing the filament performance is needed to support its sustainability. This review identified several factors that directly contribute to biochar-polymer composites' mechanical and thermal performance and biochar-reinforced 3D printing filaments for MEX, namely biochar loading, biochar type, biochar production temperatures, and compatibilizer.
2. Findings indicate that the production temperature of biochar plays a crucial role in biochar-reinforced polymers. Biochar produced at lower temperatures (<500.0 ºC) enhances mechanical strength, while higher temperatures (>700.0 ºC) improve thermal resistance. Biochar at a lower temperature contains more oxygen-containing functional groups, facilitating good adhesion with the polymer matrix. Biochar contains fewer surface functional groups when produced at higher temperatures due to biomass dehydration and deoxygenation, leading to weak adhesion between biochar and polymer.
3. Biochar exhibits higher thermal stability than polymer; increasing the biochar loadings enhances thermal stability. Polymers degrade at 126 ºC, while biochar's thermal

degradation starts at 400 ºC**,** even at minimal loading, 0.5 wt% to 0.75 wt% biochar, thermal stability improved by 1.2%.

4. Uniform dispersion of biochar allows the formation of a reinforcing network for composite structural integrity and resistance to deformation. With uniform distribution, strong mechanical interlocking, and proper biochar distribution, biochar helps resist deformation and facilitates effective load transfer. Successful biochar loading for polymer produced using molding technologies varies depending on biochar type. Wood-derived biochar (5.0 wt% to 35 wt%), by-product of fruit-derived biochar (5.0 wt% to 10 wt%), and agri-industrial waste-derived biochar (2.0 wt% to 5.0 wt%). Observed TS and FS enhancement ranges from 10.0%~100.0% while TM and FM enhancement range 10.0%~150.0%.
5. Studies on biochar application for material extrusion (MEX) are relatively new and show an increasing trend. The biochar type and percentage loading significantly influence the 3D printing filament performance. As compared to conventional manufacturing, biochar loading is relatively low. This review recommends biochar loading of 0.1 to 0.6 wt% for the by-product of fruit. However, *in situ* polymerization can achieve a higher biochar loading up to 50.0 wt%. TS, FS, and corresponding modulus enhancement can reach 50.0 %, 82.0 %, and 170.0 %, respectively.
6. Adding biochar enhances the interfacial bonding between 3D printing filaments and PBAT. With the incorporation of a compatibilizer, the successful biochar loading in PLA 3D printing filaments increases from 0.6 wt% to 1.0 wt%, demonstrating its effectiveness in promoting better dispersion and matrix–filler interaction. Minimal addition of 1.0 wt% compatibilizer yielded notable improvements in the performance without compromising their properties.

7. Sustainability analysis also highlights biochar's cost-effectiveness, carbon neutrality, and potential for closing the circular economy loop. Biochar-reinforced 3D printing filament addresses the sustainability's 6 "R" s: reduce, refuse, recycle, rethink, repurpose, and remanufacture. The life cycle assessment (LCA) also identifies biochar-reinforced 3D printing filament as potentially carbon-neutral, depending on the biochar loading. It also demonstrates a substantial reduction in environmental impacts alongside improved performance.
8. Recommendations include optimizing processing conditions, scaling sustainable feedstock supply chains, and developing standards for commercial use. Policy frameworks, carbon credits, and industry incentives are also critical for broader adoption.

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Table 1
Influence of biochar on polymer's thermal properties.

Feedstock	Pyrolysis temperature (°C)	Polymer matrix [a]	Preparation	Thermal Properties	References
Bael fruit shell	-	PP	-	• Enhanced heat resistance with 5.0 wt% biochar. • Decreased maximum rate of heat release, from 1083 KW/m^2 to 584.36 KW/m^2 for biocomposites with 7.5 wt% biochar.	Velmuruga n et al. [42]
Bamboo	500.0, 800.0, 1100.0	UHMW PE	Melt extrusion	• Improved thermal stability at higher production temperature.	Li et al. [31]
Bamboo	300.0, 400.0, 600.0, 900.0	HMP	Injection molding	• Early thermal degradation. • Improved thermal stability.	Kumar et al. [32]
Bamboo	-	PP	Melt blending and Injection molding	• Improved melting temperature by 5.9% from 160.7 °C for pure PP to166.6 °C with 10.0 wt% biochar.	Zhang et al. [37]
Bamboo	500.0	PLA	Micro-injection molding	• Early thermal degradation	Zhang et al. [113]
Bamboo	-	PLA	Injection molding	• Melting temperature from 159.8 °C to 156.7 °C with 7.5 wt% biochar.	Ho et al. [38]
Bamboo	300.0 to 500.0	PLA	Injection molding	• Enhances PLA's thermal stability in high temperature setting. • Increased crystallinity with 40.0 wt% biochar.	Zou et al. [39]

				• Strengthen flame retardant properties.	
Coconut shell	300.0, 400.0, 600.0, 900.0	HMP	Compression	• Increased thermal stability from biochar produced at 900.0 °C. • Early thermal degradation	Kumar et al. [32]
Corn Stover	550.0	PLA	Injection molding	• Melting temperature decreased from 175.7 °C to 172.6 °C at 100.0 °C with 2.0 wt% biochar.	Brdlík et al. [44]
Coffee powder	700.0	PLA	Melt mixing and Solvent casting	• Enhanced crystallinity at 2.5 wt% biochar. • Melting temperature decreased from 153.4 °C to 150.2 °C with 7.5 wt% biochar.	Arrigo et al. [114]
Date palm waste	700.0, 900.0	PP	Micro injection molding	• Decreased crystallinity.	Poulose et al. [115]
Grapevine	500.0	PLA	Compression molding	• Meting temperature decreased from 151.1 °C to 145.7 °C with 10.0 wt% biochar.	Huang et al. [116]
Pinewood (*Pinus radiata*)	500.0	PP	Injection molding	• Increased thermal stability. • Delayed onset of degradation as compared to pure PP.	Das et al. [40]
Pinewood (*Pinus radiata*)	400.0, 450.0	PP with MAPP compatibilizer	Melt extrusion and melt blending	• Improved thermal stability with 18.0 wt% biochar	Das et al. [36]
Pinewood	500.0	PP with MAPP	Injection molding	• Decreased in peak heat release rate by 50.0%. • Improved thermal stability.	Das et al. [56]

(*Pinus radiata*)		compatibilizer		• Decreased crystallinity	
Pine wood (*Pinus radiata*)	500.0	PP and MAPP compatibilizer	Melt blending	• Improved thermal stability.	Ikram et al. [117]
Pinewood (*Pinus radiata*)	900.0	PP, APP and MAPP compatibilizer	Injection molding	• Improved thermal stability.	Das et al. [118]
Pine sawdust	500.0	PP with APP and wool	Twin-screw extrusion	• Increased thermal stability.	Das et al. [53]
Poplar	450.0	PLA	Injection molding	• Stable thermal properties with 2.5 and 5.0 wt% biochar. • Biochar addition slow down the thermal degradation.	Botta et al. [119]
Rice straw	230.0	PLA	-	• Decreased melting enthalpy from 41.6 J/g to 13.9 J/g with 20.0 wt% biochar. • Slight decrease in degradation temperature as compared to neat PLA. • Higher residues yield as compared to neat PLA.	Nizamuddin et al. [45]
Wood	-	PP with graphen	-	• Improved thermal stability. • Crystallinity remains constant.	Watt et al. [57]

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[a] Polymer: UHMWPE – Ultra-high molecular weight polyethylene, PP – Polypropylene, PLA – Polylactic acid, POE – Polyolefin elastomer, MAPP – Maleic anhydride grafted polypropylene, APP – Ammonium polyphosphate, MA-g-PP – Maleic anhydride grafted polypropylene, HMP – High molecular polyethylene.

Table 2
Influence of biochar loading and biochar feedstock type on the polymer's mechanical performance.

Feedstock	Biochar (wt%)	Pyrolysis temperature (°C)	Polymer matrix [a]	Preparation	Mechanical Properties [b]	Optimal Biochar (wt%)	References
Bael fruit shell	2.5 5.0 7.5	-	PP	-	• TS: +54.7%	5.0	Velmurugan et al. [42]
Bamboo	5.0, 10.0, 15.0, 20.0, 25.0, 30.0	-	PP	Melt blending and Injection molding	• TS: +30.4% from 23.5 MPa to 30.6 MPa • TM: +109.0%	5.0 10.0	Zhang et al. [37]
Bamboo	40.0	500.0	PLA	Micro-injection molding	• FS: - 77.2% from 82.7 MPa to 18.9 MPa. • TS: - 83.8%, from 58.8 MPa to 9.6 MPa. • IS: -87.5% 17.6 kJ/m2 to 2.2 kJ/m^2 • TM: +34.2% from 0.4 GPa to 0.5 GPa • FM: + 28.5% from 3.4 GPa to 4.4 GPa.	40.0	Zhang et al. [113]
Bamboo	2.5 to 10.0	-	PLA	Injection molding	• TS: + 43.0%, from 35.8 MPa to 51.1 MPa.	7.5	Ho et al. [38]

					• TM: +34.5% from 2.9 GPa to 3.9 GPa. • FM: + 12.7%, from 700.0 MPa to 789.1 MPa • FS: + 98.9%, from 19.6 MPa to 38.9 MPa. • Ductility index: +52.0%.	10.0 10.0 7.5	
Bamboo	20.0, 30.0, 40.0, 50.0	300.0 to 500.0	PLA	Injection molding	• TS: +93.0% • FS: +29.9%	20.0	Zou et al. [39]
Bamboo	70.0	500.0, 800.0, 1100.0	UHMWPE	Melt extrusion	• TS: +91.2%, from 28.6 MPa to 54.7 MPa • TM: +161.7 %, from 826.1 MPa to 2162.6 MPa • Hardness: Shore D 61.3 to Shored D 84.3	70.0	Li et al. [31]
Bamboo	0.5, 1.0, 1.5	300.0, 400.0, 600.0, 900.0	HMP	Injection molding	• TS: +16.0% • FS: 22.0%. • FM: 25.0%.	1.0	Kumar et al. [32]
Cashew nutshell waste	5.0, 10.0, 15.0	500.0	Polyester	Resin casting	• TS: + 41.0 wt% • IS: +37.0% • Hardness: +21.0% • FS: +40.0%	10.0	Sundarakannan et al. [41]
Citron peel	0.5, 1.0,	500-800	Resin		• TS: +62.4%	2.0 vol%	Kannan et al. [43]

	2.0, 4.0 vol%				• FS: + 33.3% • IS: +47.8%		
Coconut shell	0.5, 1.0, 1.5	300.0, 400.0, 600.0, 900.0	HMP	Compression molding	• TS: +14.0% • FS: +17.0% • FM: +21.0%	1.0 wt%	Kumar et al. [32]
Corn Stover	2.0, 5.0	550.0	PLA	Injection molding	• IS: +61.0%. • TM: +11.0% from 3811.0 to 4230.0 MPa • Toughness: +61.0%	2.0 2.0 5.0	Brdlík et al. [44]
Coffee powder	1.0, 2.5, 5.0, 7.5	700.0	PLA	Melt mixing and Solvent casting	• TM: +7.5 wt% • TS: Decreased.	-	Arrigo et al. [114]
Date palm waste	5.0, 10.0, 15.0	700.0, 900.0	PP	Micro injection molding	• TM: +21.5%, from 1.1 GPa to 1.4 GPa	15.0 wt%	Poulose et al. [115]
Grapevine	1.0, 10.0	500.0	PLA	Compression molding	• TS: +41.4%, from 56.4 MPa to 79.8 MPa • TM: +45.5%, from 3.7 GPa to 5.4 GPa • IS: +40.3%, from 16.2 J/m to 22.7 J/m.	1.0	Huang et al. [116]

Maple tree	1.0, 2.0, 4.0, 20.0	600.0, 1000.0	Low viscosity epoxy resin	Resin molding	• TS: +63.0% • Elongation: +500.0% • Resiliency: +100.0%	1.0 2.0 1.0	Giorcelli et al. [33]
Pinewood (*Pinus radiata*)	15.0, 25.0, 30.0, 35.0	500.0	PP	Injection molding	• TM: +154.7%, from 1.5 GPa to 3.8 GPa • FS: +14.1%, from 51.1 MPa to 58.3 MPa at • FM: +100.6%, from 1.6 GPa to 3.3 GPa	35.0 35.0 35.0	Das et al. [40]
Pinewood (*Pinus radiata*)	6.0, 12.0, 18.0, 24.0, 30.0	400.0, 450.0	PP with MAPP compatibilizer	Melt extrusion and melt blending	• TM: +16.7%, from 3.0 GPa to 3.5 GPa. • TS: Increased.	24.0	Das et al. [36]
Pinewood (*Pinus radiata*)	24.0	500.0	PP with MAPP compatibilizer	Injection molding	• TS: +35.7% from 27.8 MPa to 37.8 MPa • FS: +4.2% from 72.1 MPa to 75.1 MPa • Hardness: Increased	24	Das et al. [56]
Pine wood (*Pinus radiata*)	24.0, 36.0	500.0	PP and MAPP compatibilizer	Melt blending	• TS: +9.4%, from 32.0 MPa to 35.0 MPa, • TM: Increased • FS: Increased	24.0	Ikram et al. [117]
Pinewood (*Pinus radiata*)	4.0, 14.0, 24.0	900.0	PP, APP and MAPP	Injection molding	• TS: +1.5% from 32.6 MPa to 33.1 MPa.	4.0	Das et al. [118]

			compatibilizer		• TM: +221.6%, from 1.5 GPa to 4.9 GPa. • FS: +24.7% from 51.0 MPa to 63.6 MPa • FM: +182.1% from 1.6 GPa to 4.6 GPa	24.0 4.0 14.0	
Pine sawdust	15.0, 20.0, 25.0	500.0	PP with APP and wool	Twin-screw extrusion	• TM: +133.0%	20.0	Das et al. [53]
Poplar	1.0, 2.5, 5.0	450.0	PLA	Injection molding	• Elastic modulus: +20.0%	5.0	Botta et al. [119]
Rice straw	5.0, 10.0, 15.0, 20.0	230.0	PLA	-	• TM: +135.3%, from 2.6 GPa to 6.2 GPa, • TS: +11.4%, from 43.7 MPa to 48.7 MPa	20.0 5.0	Nizamuddin et al. [45]
Wood	15.0, 17.0, 19.0, 19.5, 20.0	-	PP with graphene nanoplatelets and MA-g-PP	-	• TS: -19.4% from 35.0 MPa to 28.2 MPa • TM: +83.0% • FS: +40.0%, from 50.0 MPa to 70.0 MPa • FM: +57.0%	20.0 17.0 19.0 19.0	Watt et al. [57]

[a] Polymer: UHMWPE – Ultra-high molecular weight polyethylene, PP – Polypropylene, PLA – Polylactic acid, POE – Polyolefin elastomer, MAPP – Maleic anhydride grafted polypropylene, APP – Ammonium polyphosphate, MA-g-PP – Maleic anhydride grafted polypropylene, HMP – High molecular polyethylene.
[b] Mechanical Properties: FS – Flexural strength, FM – Flexural modulus, TS – Tensile strength, TM – Tensile modulus, IS – Impact strength.

Table 3
Influence of biochar as filler for additive manufacturing thermoplastic filament.

Biochar Source	Biochar (wt%)	Temperature (°C)	Polymer Matrix [a]	Filament Diameter	Mechanical Properties [b]	Optimal biochar (wt%)	Thermal Properties	References
Bamboo and continuous flax fiber	1.5, 3.0, 5.0	-	PLA	1.75	TS: +248.0% FS: +207.0%	3.0	Flame-retardant properties improved with 50.0% burning rate reduction with 3.0 wt% biochar.	Bodaghi et al. [73]
Betel nutshell	0.025, 0.05, 0.1, 0.2	500.0	PLA	1.50 to 1.75	TS: +51.1%, from 14.7 MPa to 22.3 MPa. TM: +58.2%, from 281.7 MPA to 445.5 MPa. FS: +24.5%, from 36.2 MPa to 45.1 MPa. FM: +36.4%, from 1596.5 to 2178.5 MPa.	0.1 0.1 0.0025 0.0025	Reduced degradation by 6.0%.	Arora et al. [68]
Coconut shell	0.2, 0.6, 1.0	800.0	PLA and Bioplast (23% potato starch)	1.50 to 1.75	TS: +81.9% from 8.9 MPa to 16.2 MPa TM: +510.3%, from 0.6 GPa to 3.5 GPa. Strain: Decreased from 1.8 % to 0.6 %.	0.6	Improved thermal stability. Decreased wight loss during thermal degradation.	Umerah et al. [69]
Coconut shell	1.0, 2.5, 5.0, 10.0	800.0	PLA/PBAT	1.75	TS: +45.0% TM: +18.0%	1.0 5.0	Increased melting point by 2.0 °C with at least 1.0 wt% biochar.	George et al. [120]

							Improved total crystallinity by 40.6% with 5.0 wt% biochar.	
Ground nutshell	0.025, 0.5, 0.75	700.0, 800.0, 900.0	PLA	1.65 to 1.85	TS: +39.8% TM: +17.5%	0.5	Increased melting temperature from 139.8 °C to 146.31 °C with 0.5 wt% biochar. Improved onset temperature by 10 °C and maximum degradation by 4 °C with 0.5 wt% biochar	Mandala et al. [70]
Olive tree pruning	2.0, 4.0, 6.0, 8.0	540.0	PLA	1.75	TS: +21.1%, from 45.6 MPa to 55.2 MPa. Tensile Toughness: +22.7%, from 5.3 MJ/m^3 to 6.5 MJ/m^3 FS: +14.0%, from 73.5 MPa to 83.8 MPa Flexural toughness: +8.7%, from 2.3 MJ/m^3 to 2.5 MJ/m^3, TM: +25.8% from 293.7 MPa to 369.6 MPa Impact strength: + 141.7% from 2.4 kJ/m^2 to 5.8 kJ/m^2.	2.0 2.0 4.0 2.0 and 4.0 4.0 4.0 6.0	Thermal stability remains the same.	Vidakis et al. [77]

					FM: +11.1% from 2.7 GPa to 3.0 GPa Hardness: +8.7% from 15.0 HV to 16.3 HV	8.0		
Olive tree pruning	2.0, 4.0, 6.0, 8.0, 10.0	500.0	PP	1.75	TS: +28.4% TM: + 24.3% with 4.0 wt% biochar. FS: +19.7% FM: + 27.4% Impact strength: +23.8%	4.0 4.0 6.0 6.0 6.0	Enhanced thermal stability.	Petousis et al. [72]
Olive tree pruning	2.0, 4.0, 6.0, 8.0, 10.0	500.0	HDPE	1.75	Impact strength: +28.5% TM: +29.5% from 72.7 MPa to 95.0 MPa FS: +35.6% TS: +37.8% Tensile toughness: +34.5% FM: +22.3% Microhardness: +9.1%	2.0 4.0 4.0 6.0 6.0 6.0 10.0	Enhanced thermal stability.	Vidakis et al. [79]
Olive tree pruning	2.0 4.0 6.0 8.0 10.0	540.0	ABS	1.75	TS: +24.9% TM: +25.5% Tensile toughness: +27.9% FS: +21.0% FM: +18.9% Hardness: +94.8% Impact strength: decreased as biochar loading increases.	4.0 4.0 4.0 4.0 6.0 10.0	Thermal stability remains unaffected by biochar addition.	Vidakis et al. [80]

Tomato stem	5.0 7.5	500.0	PLA	5.0	TS: -20.72% TM: -4.52% FS: +~ 39.38%	5.0	Slight increased in glass transition.	Gkiliopoulos et al. [71]
Wood	10.0, 20.0	650.0	PLA	1.75	TM: +~ 40.7% TS: +~42.5% FM: +~57.7% FS: +~55.6%	20.0	Increased crystallinity. Heat deflection temperature decreased from 62.0 °C to 57.8 °C with 10.0 wt% biochar.	Andrzejewski et al. [74]
Wood	10.0, 30.0, 50.0	550.0	PA1010		FS: +82.22% FM: +169.73%	50.0	Improved thermal stability. Maximum temperature from 460.0 °C to 474.0 °C.	Baniasadi et al. [84]
Wood	10.0 30.0 50.0	550.0	PA12		TS: +42.10% TM: +175.83%	50.0	Improved thermal stability. Maximum temperature from 456.0 °C to 467.0 °C.	Baniasadi et al. [83]
Wood	50.0	600.0	PA11		TS: +35.0% TM: +72.0%	50.0	Maximum temperature increased from 460.0 °C to 468.0 °C.	Baniasadi et al. [121]

[a] Polymer: PP – Polypropylene, PLA – Polylactic acid, PBAT – polybutylene adipate-co-terephthalate, HDPE – High density polyethylene, ABS – Acrylonitrile butadiene styrene, PA - Polyamide

[b] Mechanical Properties: FS – Flexural strength, FM – Flexural modulus, TS – Tensile strength, TM – Tensile modulus

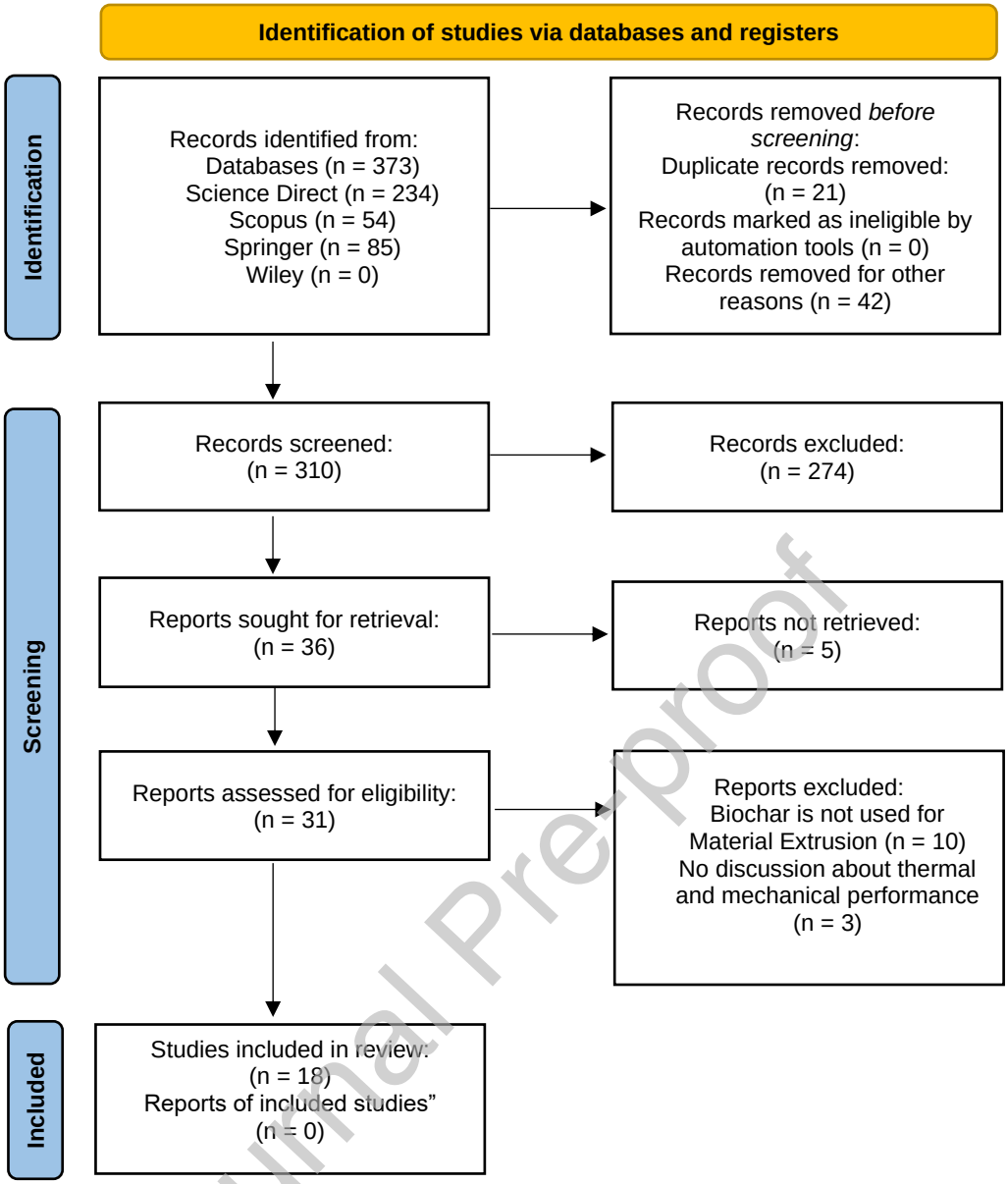


Fig. 1. PRISMA Framework for database selection.

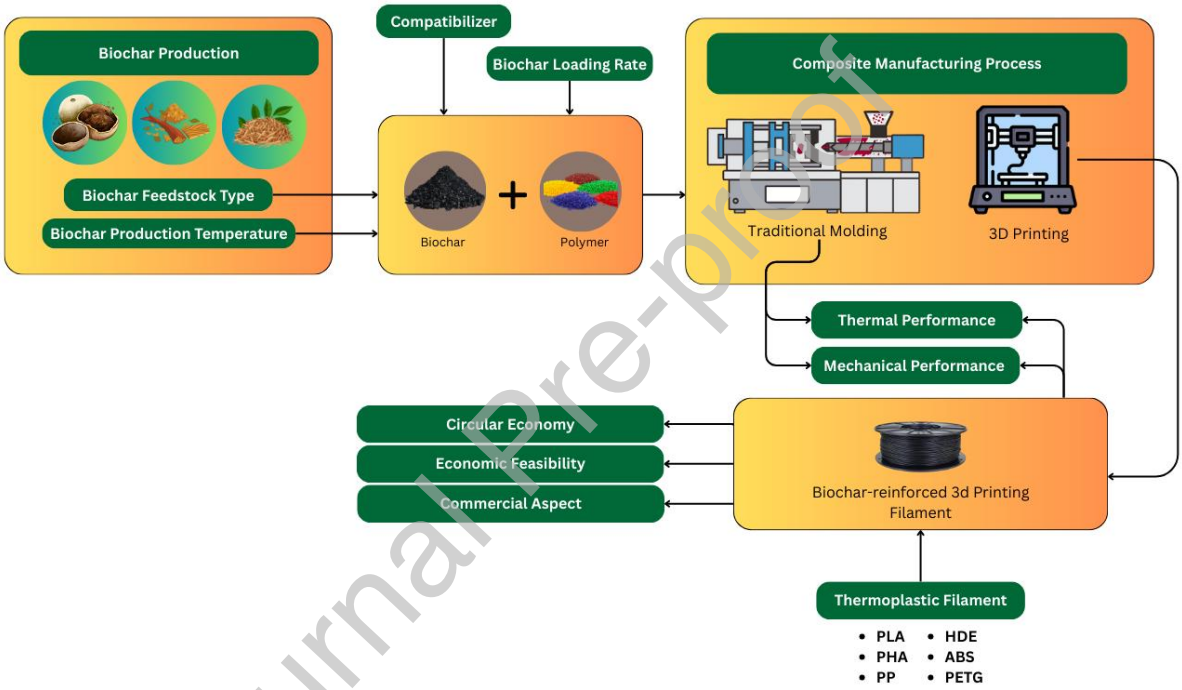


Fig. 2. Structure and scope of the review paper.

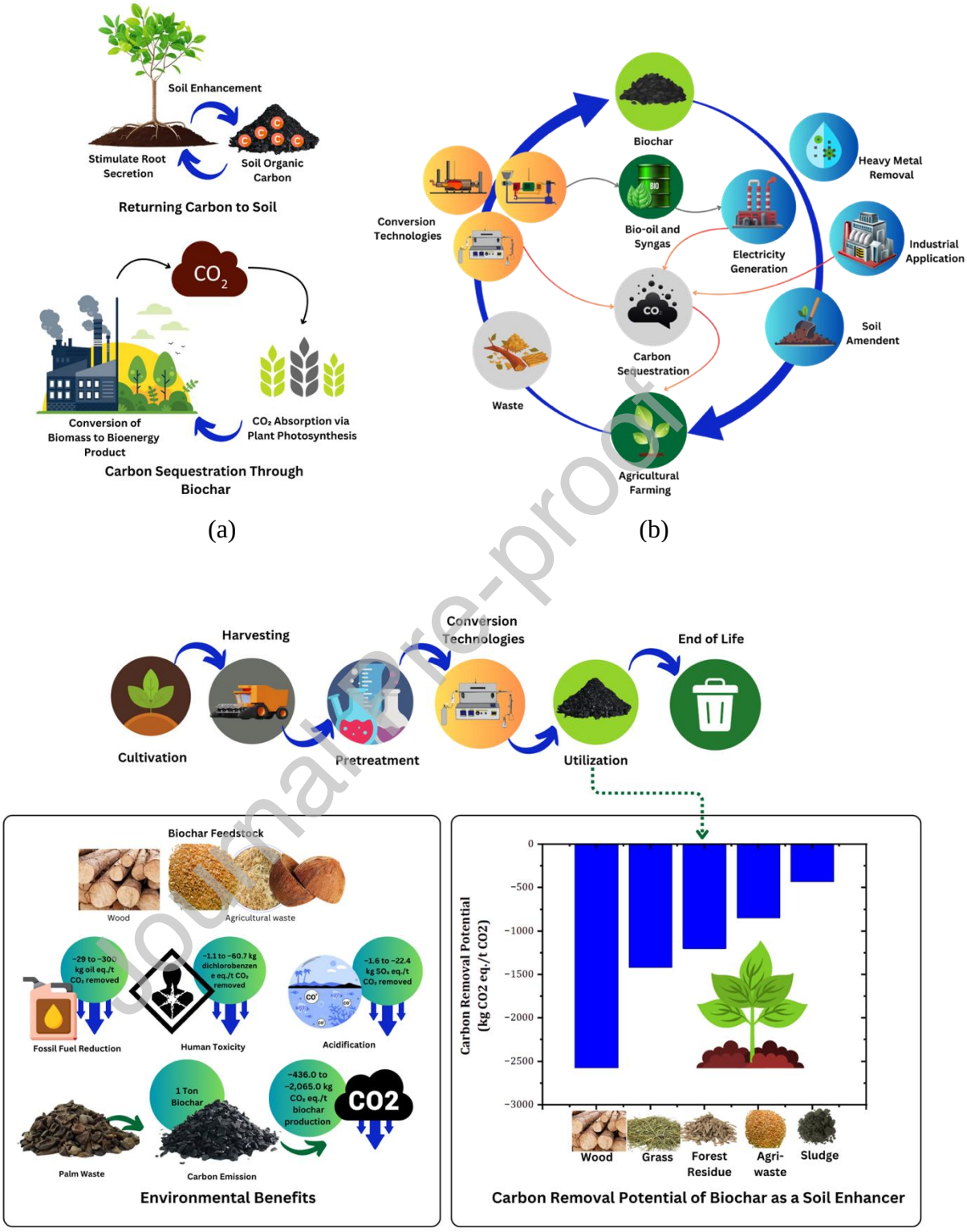
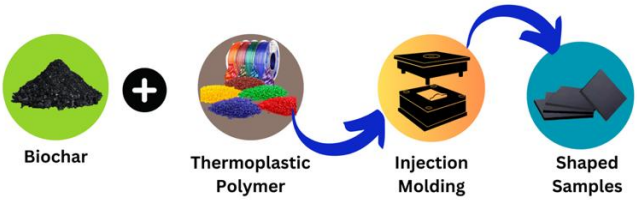
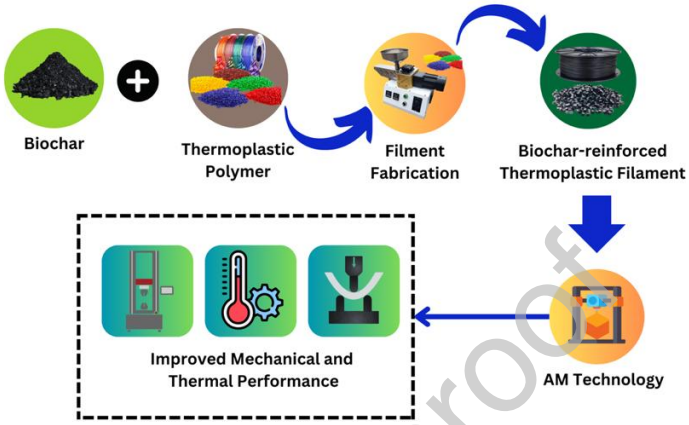


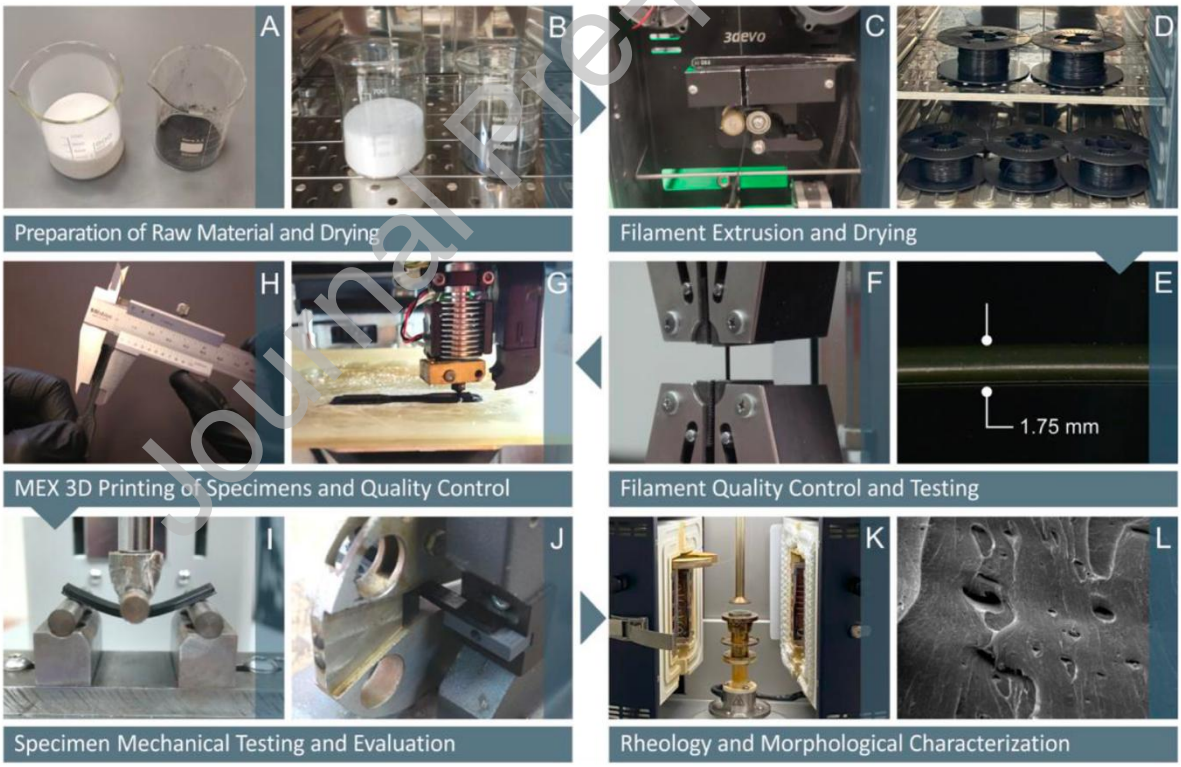
Fig. 3. Biochar (a) carbon capture, (b) circular economy, and (c) life cycle assessment.



(a)

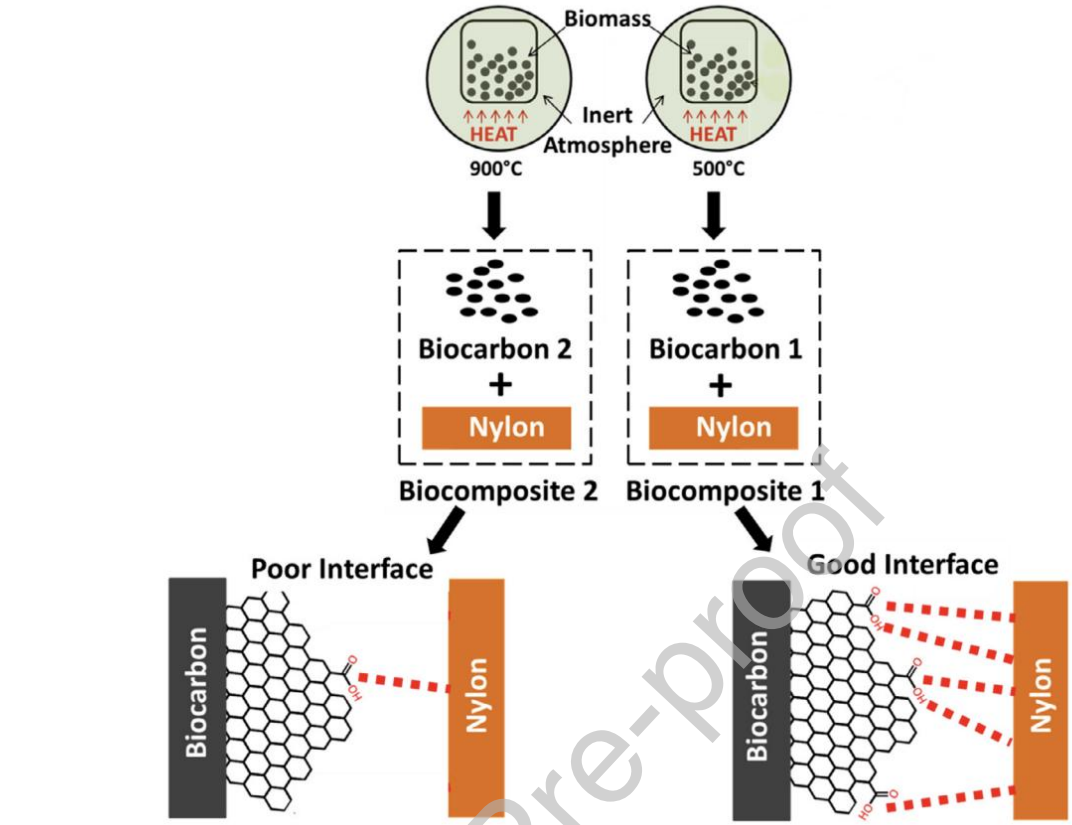


(b)

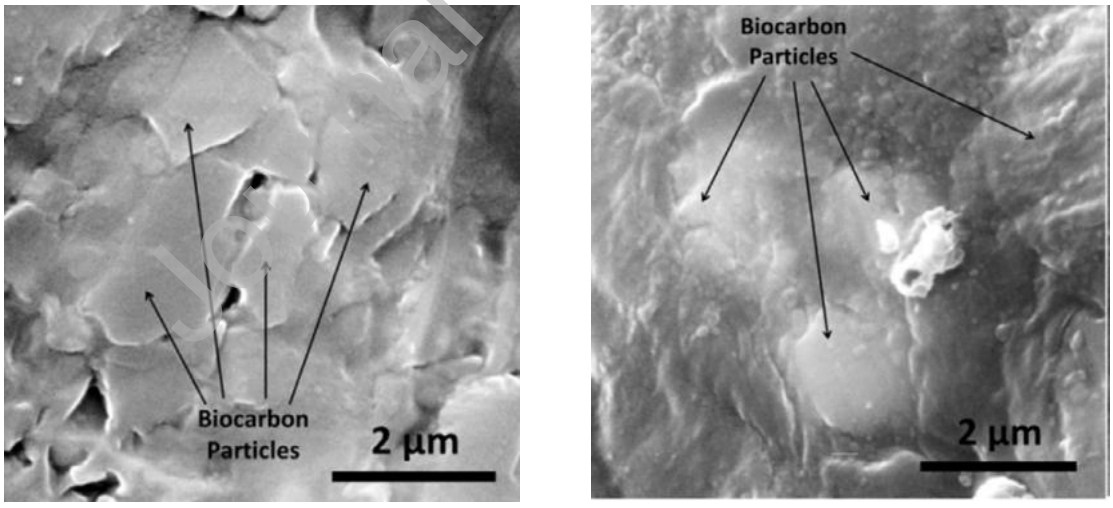


(c)

Fig. 4. Biochar-reinforced polymer process (a) injection molding, (b) additive manufacturing, (c) development and testing procedure for biochar-reinforced polymer filament. Reproduced from Vidakis et al. [79] under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).



(a)



(a) (c)

Fig. 5. (a) Visualization of biochar produced from different temperatures, highlighting different affinities with nylon. SEM Results (b) nylon with biochar produced at 900 °C, (c) nylon with biochar produced at 500 °C. Reproduced with permission under RightsLink License No. 6101280295426 from Ogunsona et al. [34].

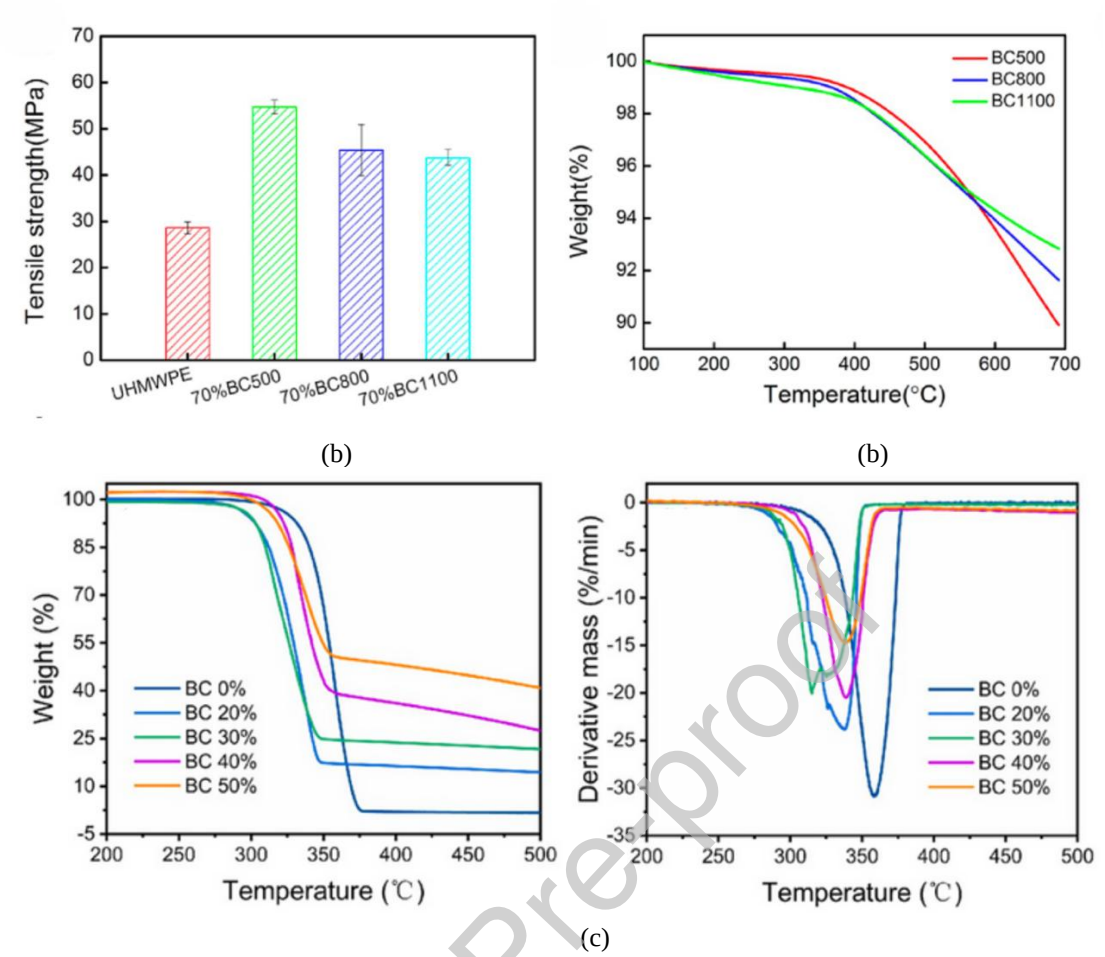


Fig. 6. Effects of biochar production temperature: (a) maximum tensile strength at different production temperatures, (b) TGA curve showing thermal stability. Reproduced with permission under RightsLink License No. 6082300107184 from Li et al. [31] Effects of biochar loading (c) TGA and DTG curves showing thermal stability at higher biochar loading. Reproduced with permission under RightsLink License No. 6082261176144 from Zou et al. [39].

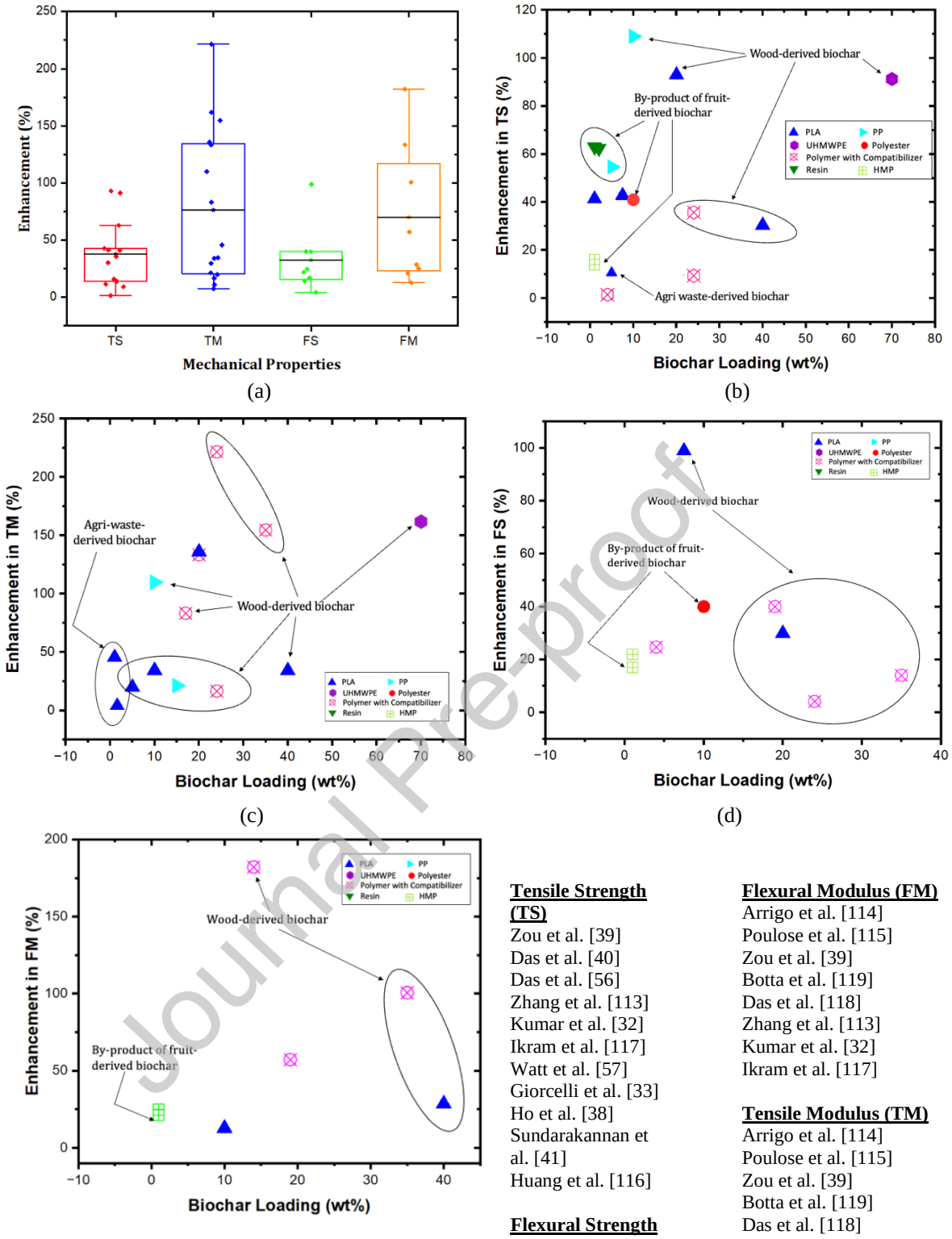


Fig. 7. Enhancement in biochar-reinforced polymer (a) mechanical (b) TS (c) TM (d) FS (e) FM.

Tensile Strength (TS)
Zou et al. [39]
Das et al. [40]
Das et al. [56]
Zhang et al. [113]
Kumar et al. [32]
Ikram et al. [117]
Watt et al. [57]
Giorcelli et al. [33]
Ho et al. [38]
Sundarakannan et al. [41]
Huang et al. [116]

Flexural Strength (FS)
Arrigo et al. [114]
Zou et al. [39]
Botta et al. [119]
Zhang et al. [113]
Kumar et al. [32]
Ikram et al. [117]
Li et al. [31]
Das et al. [56]
Zhang et al. [37]
Nizamuddin et al. [45]
Das et al. [36]
Watt et al. [57]
Das et al. [53]

Flexural Modulus (FM)
Arrigo et al. [114]
Poulose et al. [115]
Zou et al. [39]
Botta et al. [119]
Das et al. [118]
Zhang et al. [113]
Kumar et al. [32]
Ikram et al. [117]

Tensile Modulus (TM)
Arrigo et al. [114]
Poulose et al. [115]
Zou et al. [39]
Botta et al. [119]
Das et al. [118]
Zhang et al. [113]
Kumar et al. [32]
Ikram et al. [117]
Li et al. [31]
Das et al. [56]
Zhang et al. [37]
Nizamuddin et al. [45]
Das et al. [36]
Watt et al. [57]

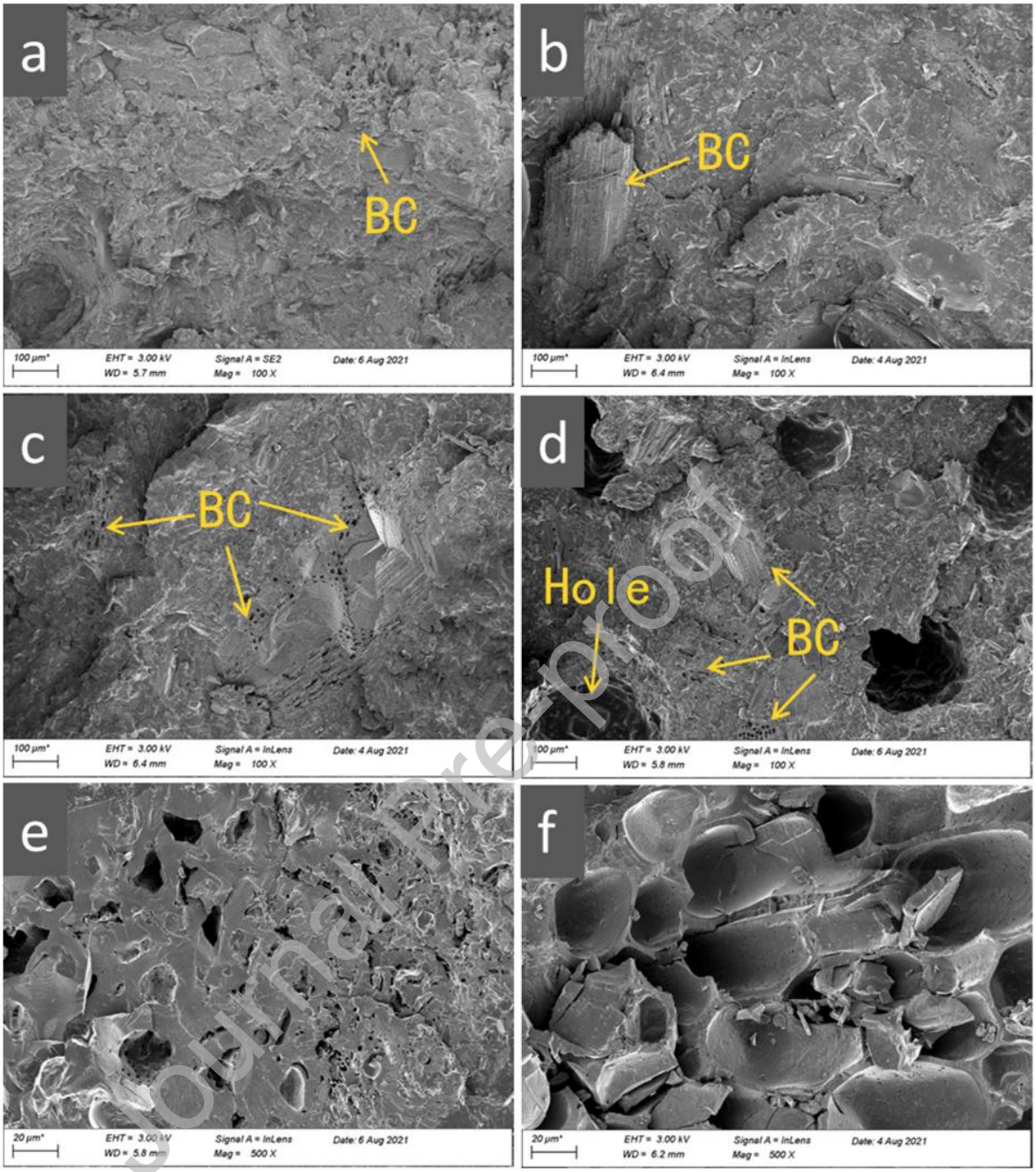
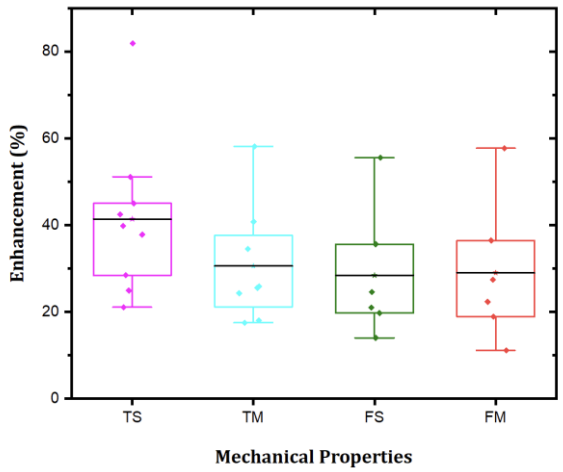
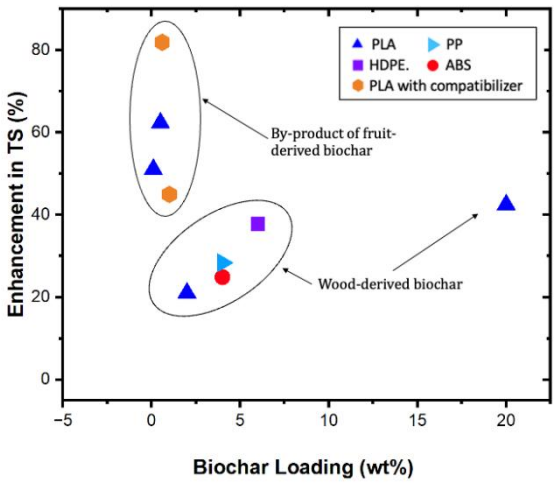


Fig. 8. SEM images of the tensile section of biochar-reinforced PLA composite at biochar varying loading (a) 20wt%, (b) 30 wt%, (c) 40 wt%, (d) 50 wt%, (e) Bamboo charcoal in BC/PLA at 40 wt% (f) Bamboo charcoal in BC/PLA at 50 wt%. Reproduced with permission under RightsLink License No. 6082261176144 from Zou et al. [39].



(a)



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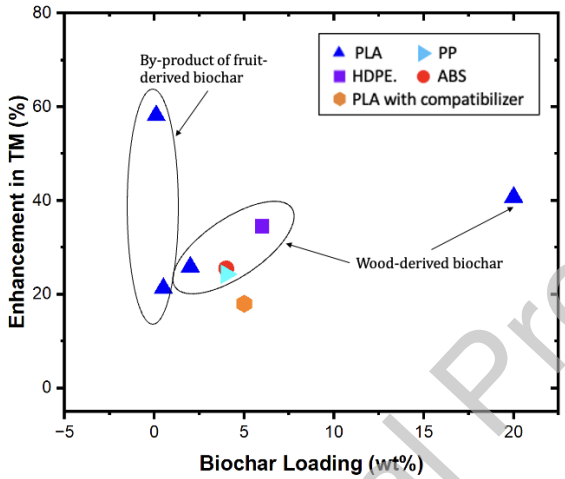
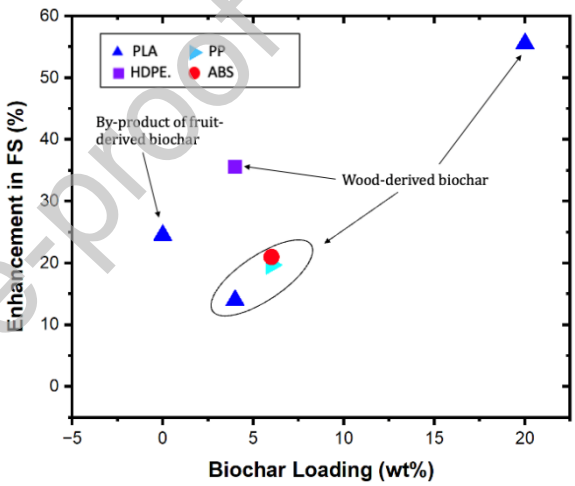
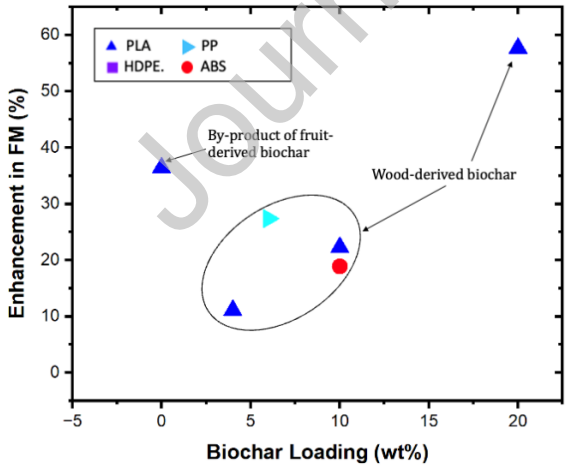


(c)



(d)



(e)

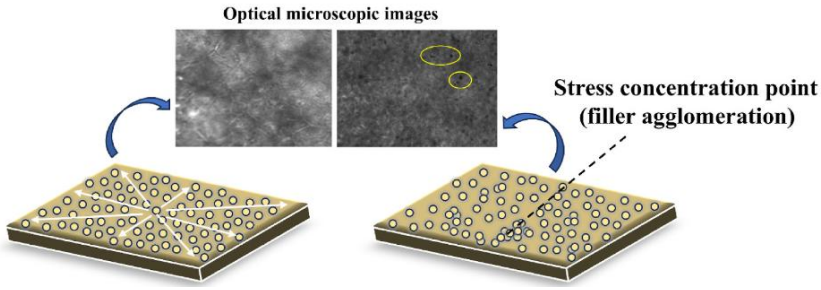
Fig. 9. Enhancement in biochar-reinforced thermoplastic filament (a) mechanical properties (b) TS (c) TM (d) FS (e) FM.

Tensile Strength (TS)
Bodaghi et al. [73]
Umerah et al. [69]
George et al. [120]
Mandala et al. [70]
Andrzejewski et al. [74]
Arora et al. [68]
Petousis et al. [72]
Vidakis et al. [79]
Vidakis et al. [80]
Vidakis et al. [77]

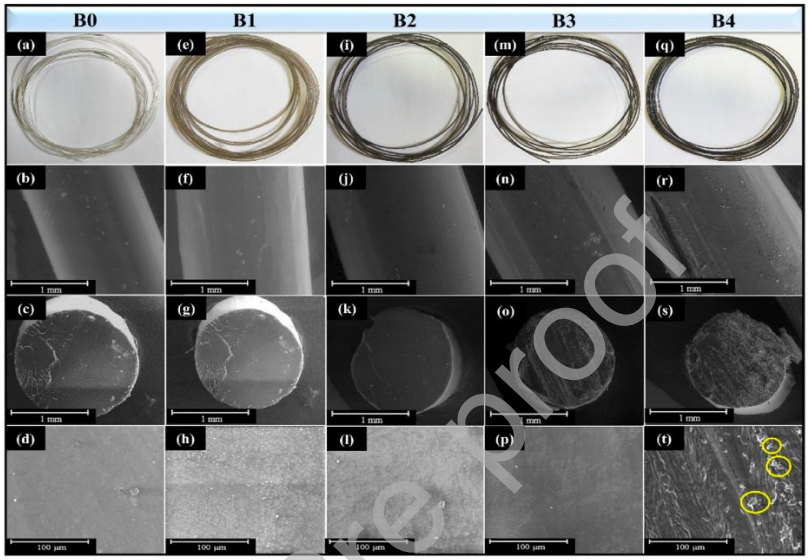
Tensile Modulus (TM)
Andrzejewski et al. [74]
Arora et al. [68]
Petousis et al. [72]
Vidakis et al. [79]
Vidakis et al. [80]
Vidakis et al. [77]

Tensile Modulus (TM)
Umerah et al. [69]
George et al. [120]
Mandala et al. [70]
Andrzejewski et al. [74]
Arora et al. [68]
Petousis et al. [72]
Vidakis et al. [79]
Vidakis et al. [80]
Vidakis et al. [77]

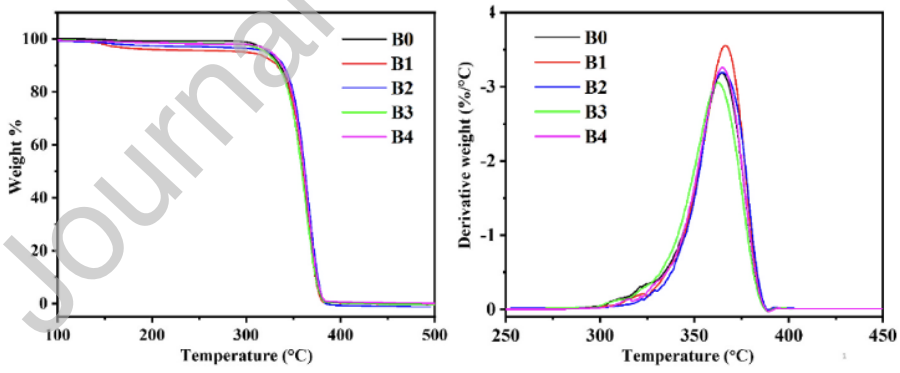
Flexural Strength (FS)
Bodaghi et al. [73]
Andrzejewski et al. [74]
Arora et al. [68]
Petousis et al. [72]
Vidakis et al. [79]
Vidakis et al. [80]
Vidakis et al. [77]



(a)



(b)



(c)

Fig. 10. (a) Load distribution showing uniformly dispersed biochar (left) and non-uniform dispersion (right). Reproduced with permission under RightsLink License No. 6104710774029 from Arora et al. [68] (b) SEM images of filament samples with vertical and cross-sectional views. B0-Pure PLA (a,b,c,d), B1-PLA with 0.025 wt% biochar (e,f,g,h), B2- B1-PLA with 0.05 wt% biochar (i,j,k,l), B3- B1-PLA with 0.10 wt% biochar (m,n,o,p), and B4- B1-PLA with 0.20 wt% biochar (q,r,s,t). Reproduced with permission under RightsLink License No. 6082930726150 from Arora et al. [68] (c) Thermogravimetric analysis - reduction in weight % (left) derivative weight % (right). RightsLink License No. 6085800722087 from Arora et al. [68].

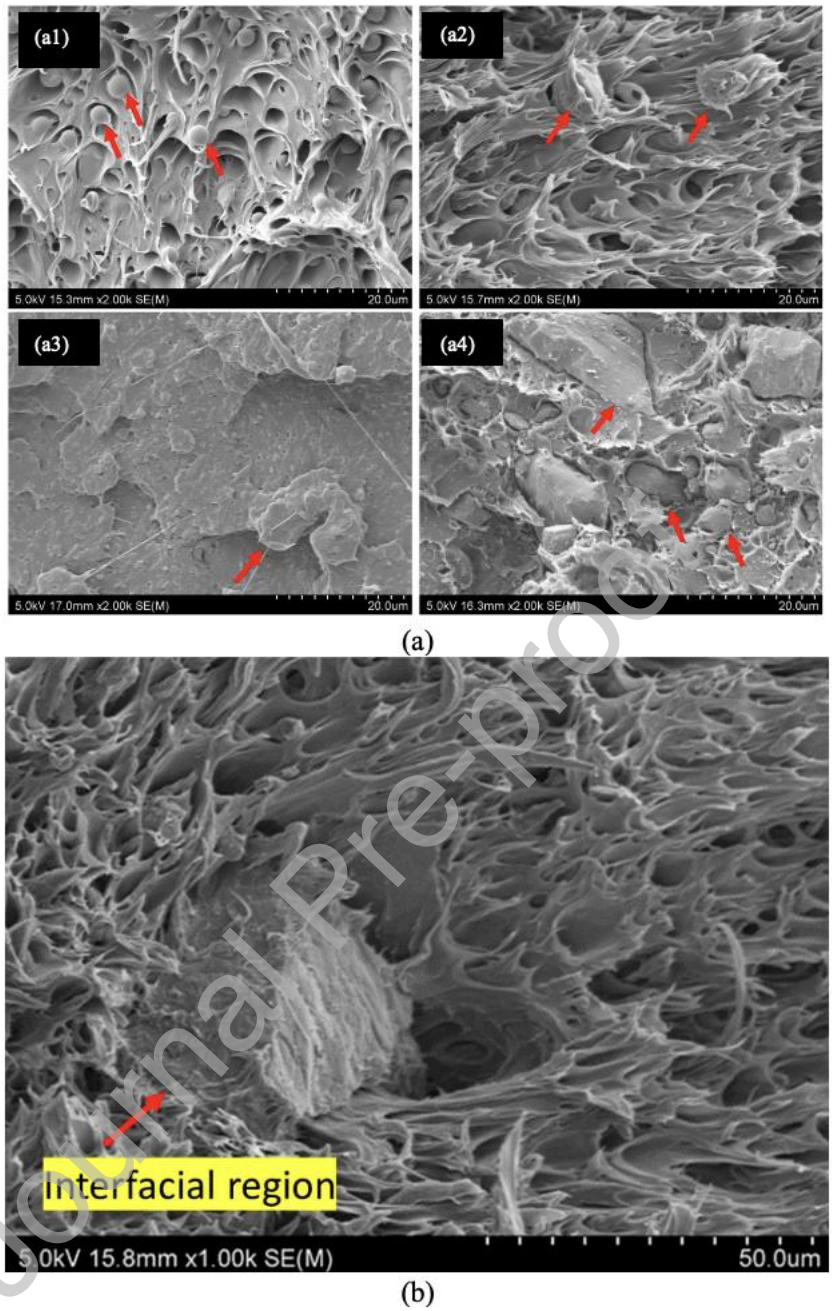


Fig. 11. SEM images with red arrows indicating the PBAT phase in the matrix (a) Images of fractured surfaces (a1) PLA (80%)/PBAT (20.0%) (a2) PLA (79.0%)/PBAT(20.0%)/BC (1.0%) (a3) PLA (77.5%)/PBAT(20.0%)/BC(2.5%) (a4) PLA(70.0%)/PBAT(20.0%)/BC (10.0%) (b) PLA and PBAT interfacial adhesion in PLA (79.0%)/PBAT(20.0%)/BC (1.0%). Reproduced from George et al. [120] under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

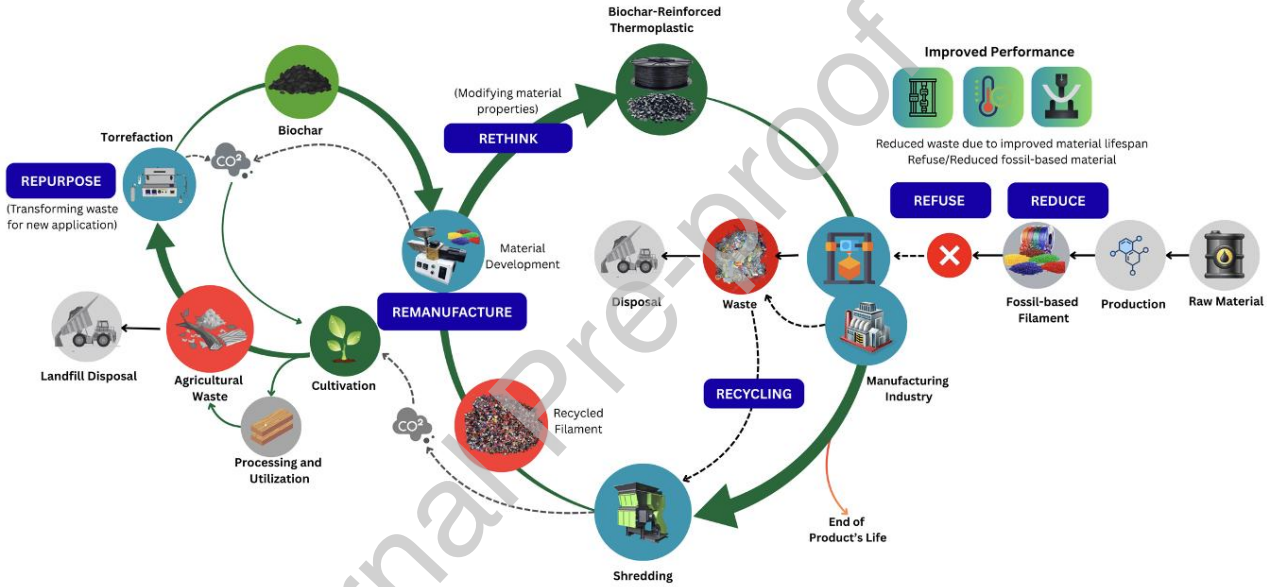
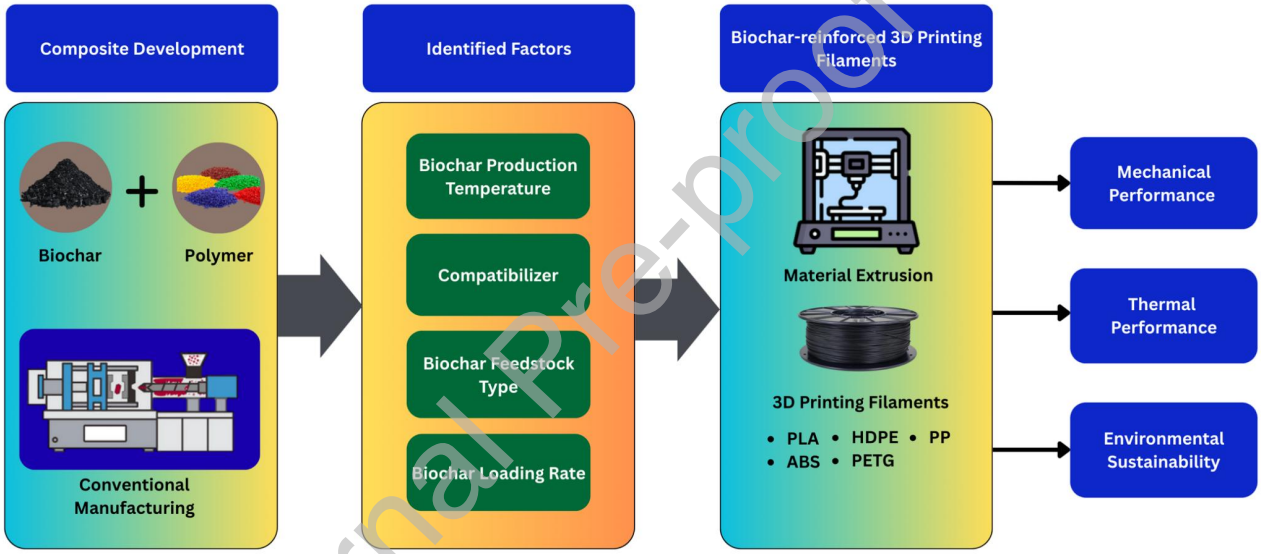


Fig. 12. Biochar-reinforced polymer composite in circular economy

Graphical Abstract



Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: