

Synergistic enhancement of fire performance and carbon footprint reduction in polymer biocomposites through combined use of lignin and biochar

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ABSTRACT

Biomass-derived materials are increasingly being incorporated into plastics to create biocomposites that reduce reliance on fossil-based feedstocks and lower carbon footprints. Maximizing the sustainability potential of these bio-based materials requires increasing their content within polymer matrices. However, a significant challenge arises: as bio-based content increases, performance trade-offs often arise. This study addresses this issue by examining the combined use of multiple bio-based components, specifically lignin and biochar, in acrylonitrile-butadiene-styrene (ABS) biocomposites. The bio-based content reached up to 44 wt%, while retaining adequate processability for extrusion and vacuum forming, as demonstrated by producing a miniature roof box sample. With this biocomposite composition, greenhouse gas emissions could be reduced by up to 40 %. Moreover, the fire performance was slightly improved by adding either lignin or biochar alone, while the combination of both fillers improved the fire performance significantly (a peak heat-release rate being half of that of ABS) due to a synergistic barrier-forming effect, limiting the transport of oxygen and fuel to the heat source and reducing heat transfer. The inclusion of both biochar and lignin influenced the mechanical properties of the composite, leading to an increase (33 %) in stiffness but a slight reduction (22 %) in strength. This study suggests that combining biochar and lignin can maximize bio-based content while improving critical performance characteristics, offering a viable pathway for more sustainable plastics.

1. Introduction

Advancements in more sustainable sourcing of materials in all sectors go hand in hand with nationwide set goals of net-zero greenhouse gas emissions by 2050, for example to combat climate change (European Commission, 2023; Pauliuk et al., 2021; Wei et al., 2024). One approach to reducing the carbon footprint of these petroleum-based polymeric materials is to incorporate bio-based materials or fillers (Chang et al., 2020; Das et al., 2015; Källbom et al., 2022; Rosenboom et al., 2022; Yang et al., 2024). Bio-based fillers offer several advantages in reducing

carbon emissions: i) their production typically consumes less energy than petroleum-based polymers (Zuiderveen et al., 2023); ii) using plant-based materials helps offset some of the emissions since plants absorb carbon dioxide during their growth, contributing to a more carbon-neutral lifecycle (Rosenboom et al., 2022; Zuiderveen et al., 2023); iii) bio-based fillers are often biodegradable, which reduces long-term environmental impact by minimizing waste and promoting sustainability. This shift decreases reliance on non-renewable resources and fosters a more eco-friendly approach to material development and usage.

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Among bio-based fillers, biochar and lignin have attracted increasing attention for their environmental benefits and functional properties (Bajwa et al., 2019; Das et al., 2016; Patel et al., 2024; Yang et al., 2024; Zhang et al., 2024). Biochar is the char produced by breaking down organic substances from biomass in a low-oxygen environment in the temperature range of 350–1000 °C (Patel et al., 2024). The specific properties of biochar depend on the biomass feedstock and pyrolysis conditions, but it is a carbon-rich biomaterial, and displays a high surface area and a rich porous structure (Patel et al., 2024). Lignin, on the other hand, is a natural polymer found in plants' cell walls, providing strength and rigidity. It is the second most abundant biopolymer after cellulose and is widely available as a byproduct of the pulp and paper industry (He et al., 2022).

Efforts to integrate biochar and lignin into polymer matrices have shown promising results, not only in terms of environmental sustainability but also in improving certain properties of plastics (Li et al., 2023; Niu et al., 2023; Prieur et al., 2016; Wu et al., 2021; Xiao et al., 2023; Yang et al., 2024). For example, biochar has been demonstrated to enhance stiffness (Das et al., 2016) and electrical conductivity (Das et al., 2021), while lignin acts as a UV light blocker and antioxidant (Niu et al., 2023; Yang et al., 2024). Importantly, both biochar and lignin have been proven to enhance the flame retardancy of polymers (Das et al., 2016; Prieur et al., 2016; Wu et al., 2021). Biochar, when incorporated into a polymer matrix, forms a thermal barrier during combustion by creating a protective char layer on the material's surface, which reduces heat transfer and slows down burning (Das et al., 2016). Lignin also improves flame retardancy through its aromatic structure and high carbon content, forming a stable char layer during combustion, which further insulates the material from heat and oxygen (Niu et al., 2023; Prieur et al., 2016; Wu et al., 2021).

To fully capitalize on the sustainability potential of biofillers, increasing their content in polymer matrices is a critical step. However, there is a practical limit to the amount of biofillers that can be incorporated without compromising key material properties. Research by Das et al. (Das et al., 2015) suggests that the optimal biochar content in plastic composites is around 10 wt%, as higher concentrations tend to degrade key properties such as ductility (Das et al., 2016).

To overcome these limitations and further enhance sustainability, this study investigates the feasibility of incorporating multiple bio-based components together to fabricate polymer biocomposites. Acrylonitrile butadiene styrene (ABS), a commonly used thermoplastic polymer in e. g., the automotive industry (Greene, 2021), was selected as the model polymer in this study. By combining both biochar and lignin into ABS, we aim to develop a material that not only maximizes the use of sustainable biofillers but also maintains or enhances key properties such as processability, thermal stability, and stiffness. As both biochar and lignin have been individually shown to improve fire performance, a key focus of this study is to explore whether their combined effects can provide a synergistic improvement in fire resistance, making the

material more suitable for high-performance applications.

2. Materials and methods

2.1. Materials

Acrylonitrile butadiene styrene (ABS) granules with a tradename SENOSAN® AM53C SOLAR EG and a density of 1.06 kg m⁻³ were supplied by Senoplast Nordic AB, Sweden. A modified lignin material, RENOL®, was supplied by Lignin Industries, Sweden, and the modification process for Renol lignin was described in Ref. (Avella et al., 2023). Biochar pellets made from agricultural by-products (seed husks) by a pyrolysis process were purchased from Skånefrö AB, Sweden.

2.2. Sample preparation

The sample preparation processes are illustrated in Fig. 1.

2.2.1. Milling and mixing

An ABS/lignin matrix sample was prepared by blending the as-received ABS and Renol lignin in a 70/30 mass ratio using a twin-screw extruder/compounder (Xplore Instruments, the Netherlands). The extrusion process involved a temperature profile of 190–250 °C from the feeding zone to the die. The extruded filaments were then pelletized.

The pellets of ABS, ABS/lignin, and biochar were cryo-ground in a rotor mill (Retsch ZM200, Germany). Liquid N₂ was used for cooling during the grinding. The rotor mill was operated at a speed of 14 000 rpm equipped with a 1 mm trapezoid sieve for the ABS and ABS/lignin, and at 10 000 rpm fitted with a 0.25 mm trapezoid sieve for the biochar as this produced the most consistent powders. The obtained powders were dried in a desiccator containing silica gel for a minimum of 48 h before further processing.

The dried powders were manually mixed into ABS/biochar and ABS/lignin/biochar samples, to which biochar was added from 0 to 20 wt% in increments of 5. For brevity, ABS and ABS/lignin mixed with X wt% biochar were labeled as AX and ALX, respectively, as shown in Table 1. For instance, the biocomposite containing ABS/lignin with 20 wt% biochar was named AL20. By incorporating both bio-based materials, the total bio-based content in the resulting ABS/lignin/biochar composite ranged from 30 to 44 wt% (Fig. 2).

To demonstrate the scalability of the materials, melt compounding was performed using an industrial-scale twin-screw extruder at Norner, a company based in Norway. The extruded filaments were pelletized and further extruded into 1 mm thick sheets.

2.2.2. Compression moulding

The mixed samples were then pressed into square sheets (280 × 250 × 1.5 mm) using a compression molder (Fontijne Presses TP

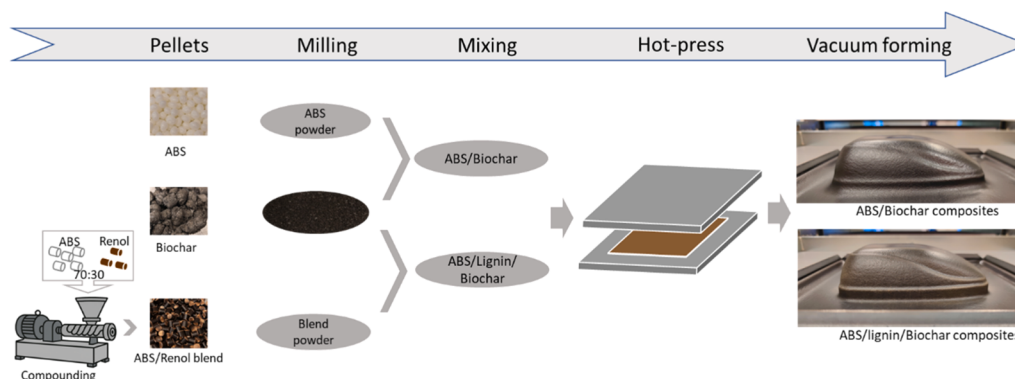


Fig. 1. Illustration of the sample preparation.

Table 1

Composition of prepared samples with varying biochar content in ABS and ABS/Renol (70/30) matrices.

Sample name	Matrix	Biochar Content (wt%)
A0	ABS	0
A5	ABS	5
A10	ABS	10
A15	ABS	15
A20	ABS	20
AL0	ABS/Renol (70/30)	0
AL5	ABS/Renol (70/30)	5
AL10	ABS/Renol (70/30)	10
AL15	ABS/Renol (70/30)	15
AL20	ABS/Renol (70/30)	20

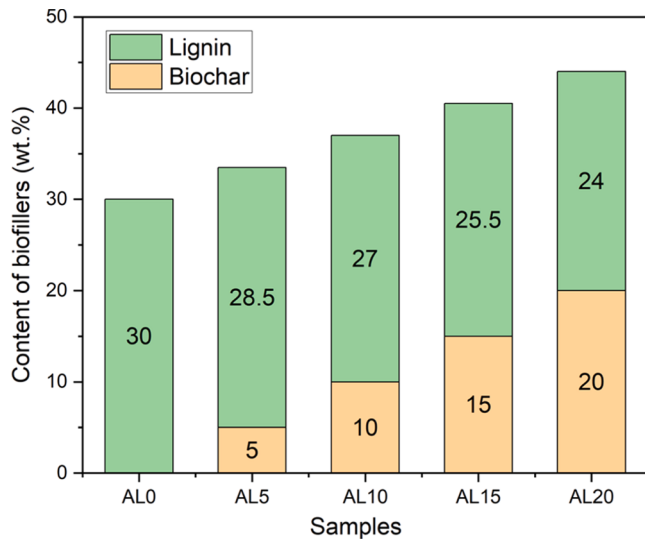


Fig. 2. Bio-based content (lignin and biochar) in the ABS/lignin/biochar biocomposites.

400, the Netherlands). The compression moulding was carried out as a three-step process: 1) preheating from 180 to 200 °C with a force of 20 kN for 7 min, 2) compression (200 °C, 150 kN, 5 min), 3) cooling (from 200 °C to 20 °C, 150 kN, 8 min). In addition, thinner sheets (0.5 ± 0.1 mm thick) were also prepared with the same processing parameters, and dumbbells (ISO 37–3), used for tensile testing, were cut from the thin sheets by a cutting die (Elastocon AB, Sweden).

2.2.3. Vacuum forming

As ABS is widely used in the automotive industry, the prepared ABS biocomposites were used to produce a miniature roof box via vacuum forming to determine its processability. The compression-molded sheets were first clamped in a vacuum-forming machine (Formech 508DT, UK) and heated using quartz infrared heating elements at 210 °C (70 % of maximum capacity) for ca. 1 min, where they became soft and workable. The heating source was removed, and a lever elevated the vacuum-forming mold to the sheet. A vacuum was applied until the material had taken the final form, and the sample was left on the form until it had cooled down to ambient temperature. The vacuum forming was performed until three replicates of the proper form for each sample were obtained.

2.3. Characterizations

2.3.1. Scanning electron microscopy (SEM)

The morphology of the composite samples was observed in a table-top scanning electron microscope (Hitachi TM-1000). Samples for SEM were first cryo-fractured from liquid nitrogen and then dried in a

desiccator containing silica gel. By the use of low voltage and vacuum, no sputtering was required. The morphology of ground biochar was examined with a field-emission scanning electron microscope (Hitachi S-4800). The energy dispersive spectroscopy (EDS) images/spectra were collected from an 80 mm X-Max Large Area Silicon Drift Detector sensor (Oxford Instruments Nanotechnology) and were evaluated using AZtec INCA software.

2.3.2. Tensile tests

Tensile tests were performed at 23 °C and 50 % RH in an Instron 5944 Universal Tensile Testing Machine with a 500 N load cell, according to ISO 527. The dumbbells were strained at a crosshead speed of 10 mm/min with an initial gauge length of 25 mm. Five replicates were tested for each sample. The samples were first conditioned at 23 °C and 50 % RH for 48 h before the tests. The maximum tensile stress was reported as the tensile strength of the samples.

2.3.3. Thermogravimetry (TG)

Specimens of 10 ± 0.5 mg, cut from the prepared sheets, were measured with a TG/DSC 1 (Mettler-Toledo, Switzerland). The specimen was heated in a 70 µL alumina crucible from 30 to 600 °C with a rate of 10 °C min⁻¹ and a nitrogen gas flow rate of 50 ml min⁻¹.

2.3.4. Differential scanning calorimetry (DSC)

Calorimetry data were obtained using a DSC (Mettler Toledo DSC1, Switzerland). 5 ± 0.5 mg specimens were cut out from the sheets and placed in 40 µL alumina cups. The samples were first heated to 200 °C at a rate of 10 °C/min and held at 200 °C for 2 min, then cooled to –30 °C at a rate of 10 °C/min. All these processes were carried out under a nitrogen atmosphere (gas flow of 50 ml/min).

2.3.5. Cone calorimetry

Square samples measuring 2 × 2 × 1 cm³ were cut from the compression-molded samples for the cone calorimetry test. The experiments followed the guidelines outlined in ISO 5660 standards and were performed using a cone calorimeter (Netzsch TCC 918, Germany). These tests were conducted at a heat flux of 25 kW/m². Due to smoke emission, the distance between the cone heater and the sample surface was maintained at 60 mm rather than the typical 25 mm.

2.3.6. UL94 vertical burning test

Bar specimens (125 mm in length and 13 mm in width) were cut from the flat edge area of the vacuum-formed samples for the UL 94 burning test. Before test, the specimens were conditioned at 23 °C and 50 % relative humidity for 48 h. Each specimen was mounted vertically ca. 300 mm above a cotton layer and the burner with flame (ca. 20 mm high) was applied with a 45° angel at the bottom of the specimen for 10 s. Three specimens were tested for each material instead of five, as the samples did not meet the rating criteria.

2.3.7. Water uptake

Square samples (ca. 1 × 1 cm) were cut from the sheets and placed in plastic vials filled with distilled water. The water sorption of the samples at room temperature was determined gravimetrically using a Mettler-Toledo balance (AG245, Mettler-Toledo, Switzerland). Before being weighed on the balance, the wet samples were quickly blotted with a paper tissue to remove the free water on the sample surface. Three replicates were tested for each sample.

2.3.8. Fourier transform infrared (FTIR)

The spectra of the composite sample and ground biochar particles were recorded (32 scans, 4 cm⁻¹ resolution) on a PerkinElmer Spotlight 400 (USA) equipped with a single attenuated total reflection accessory (Golden Gate, Graseby Specac, UK).

2.4. Carbon footprint assessment

The carbon footprint of the blends of ABS, lignin and biochar were assessed as greenhouse gas (GHG) emissions from their production and end-of-life carbon release. The assessment was carried out based on the proportions of the components used in production (Fig. 2) and corresponding emission data (Table S1) for material production and material end-of-life combustion with only fossil carbon accounted for. Potential differences in process parameters and resulting carbon emissions were assumed negligible and were therefore left out from the assessment.

3. Results and discussion

3.1. Biochar

Fig. 3 shows that the biochar particles exhibited a wide length distribution, ranging from a few micrometers up to approximately 140 micrometers, with an average length of around 31.4 μm . The SEM image revealed a highly porous structure (Fig. 3c). EDS analysis confirmed the presence of oxygen in the biochar, with an oxygen content of about 10.4 % (Fig. 3e and f). The presence of oxygen was further supported by FTIR results, showing a peak at 1034 cm^{-1} , which was assigned to C–O stretching vibrations (Fig. 3g). This suggests the existence of residual

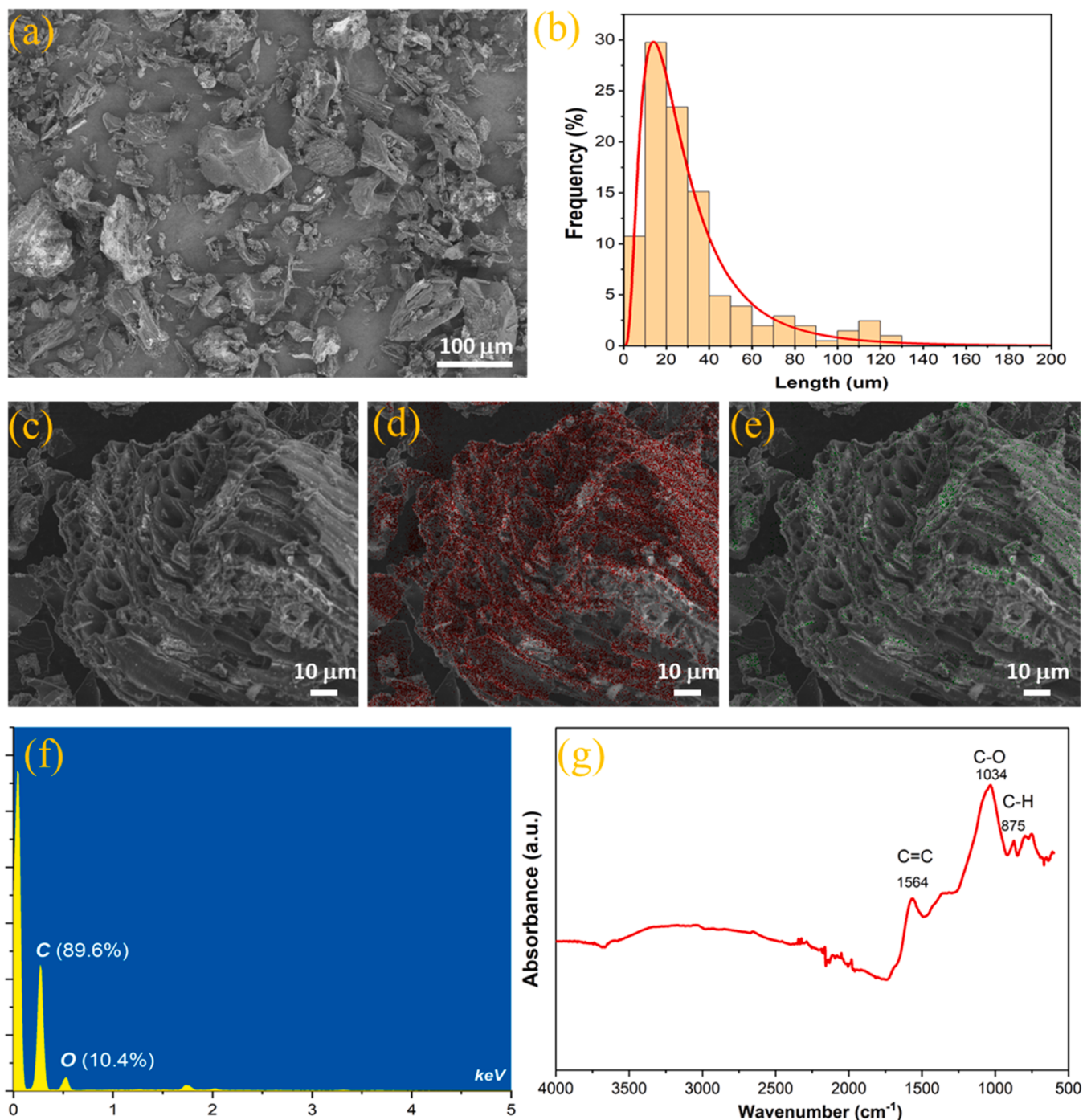


Fig. 3. Characterization of biochar: (a) SEM image of biochar particles; (b) Particle size distribution (length); (c) Original SEM-EDS image of the biochar particle; (d) Elemental distribution map of carbon (C); (e) Elemental distribution map of oxygen (O); (f) Corresponding EDS spectrum; (g) FTIR spectrum of biochar.

oxygenated groups, such as esters, alcohols, or ethers, remaining in the biochar after pyrolysis.

3.2. Processability and scalability of the biocomposites

All samples were possible to vacuum form, where their sheets underwent significant deformation under elevated temperatures (Fig. 4a). Incorporating lignin resulted in a brown coloration of the ALO sample, whereas adding biochar imparted a darker shade to both matrix samples. Besides, the A0 and ALO samples exhibited the most desirable surface finish, appearing glossy, and adding biochar resulted in a marginally less glossy and slightly rougher surface texture. Nevertheless, there were no observable biochar particles on the surfaces, and the uniformity in color and appearance indicated that both lignin and biochar were uniformly distributed in the ABS.

The respective compositions were also compounded using a twin-screw extruder to assess the feasibility of large-scale production of the biocomposites. Fig. 4b showcases representative pellets obtained after the extrusion process, which were subsequently utilized for sheet extrusion. An example of the extruded sheet is presented in Fig. 4c. These trials demonstrated the good processability and scalability, indicating that the materials are suitable for various processing methods such as sheet extrusion and vacuum forming on a large scale.

The melt flow index (MFI) test revealed that the addition of biochar fillers increased the MFI of ABS, likely due to the presence of graphitic surfaces on the biochar (Fig. S1). These surfaces can act as internal lubricants, facilitating polymer chain mobility and enhancing melt flow. The incorporation of lignin exhibited an even more pronounced effect on increasing the MFI of ABS. This is attributed to the presence of bio-oil components within Renol lignin, which can act as natural plasticizers with inherently low viscosity (Avella et al., 2023). The improved flowability of the composites suggests that they can be processed at lower temperatures compared to neat ABS, offering potential benefits in terms of energy savings and thermal stability during manufacturing.

3.3. Morphology of the biocomposites

Studies (Nguyen et al., 2018; Song et al., 2012) have shown that ABS is immiscible with lignin. Their blends show a sea-island morphology where the minor lignin phase disperses as droplets in the ABS matrix and the dispersed lignin droplets have sizes smaller than 2 μm (Fig. S2). Fig. 5c and e suggest that the degree of dispersion of the biochar particles was relatively good. Despite the biochar being incorporated through powder mixing instead of melt compounding, the dispersion was enhanced by grinding the biochar into particles smaller than 250 μm before mixing. The good dispersion of biochar accounted for the homogeneous coloration of the vacuum-formed samples presented in Fig. 4a. The biochar particles were firmly bonded to the ABS matrix (Fig. 5d and e), suggesting their good interfacial adhesion. Besides, the molten ABS matrix infiltrated the pores of the biochar particles during the compression moulding (Fig. 5e). This pore infiltration could lead to large networks of mechanical interlocking between the matrix and the biochar particles and thus was beneficial for improving the mechanical properties of the resulting biocomposites (Das et al., 2016).

3.4. Thermal properties

Fig. 6 shows that the glass transition temperature of the styrene component (T_g) was 106 $^{\circ}\text{C}$ for the neat ABS sample, and with the inclusion of lignin, it decreased to 95 $^{\circ}\text{C}$ (ALO). This reduction in T_g can be attributed to the plasticizing effects of the low molecular compounds present in lignin. These compounds migrate into the ABS matrix during compounding and lower the glass transition temperature of ABS. Fig. 6 also shows that the effects of biochar on the T_g of ABS were negligible.

The samples containing lignin started to decompose at a lower temperature than those without lignin during heating (Fig. 7a). Specifically, the decomposition temperature, here defined as the temperature at which a 5 % weight loss occurred, decreased by 50 $^{\circ}\text{C}$ from 390 to 340 $^{\circ}\text{C}$, with the addition of 30 wt% lignin (relative to the mass of ABS). The shift of the decomposition peak towards a lower temperature after the

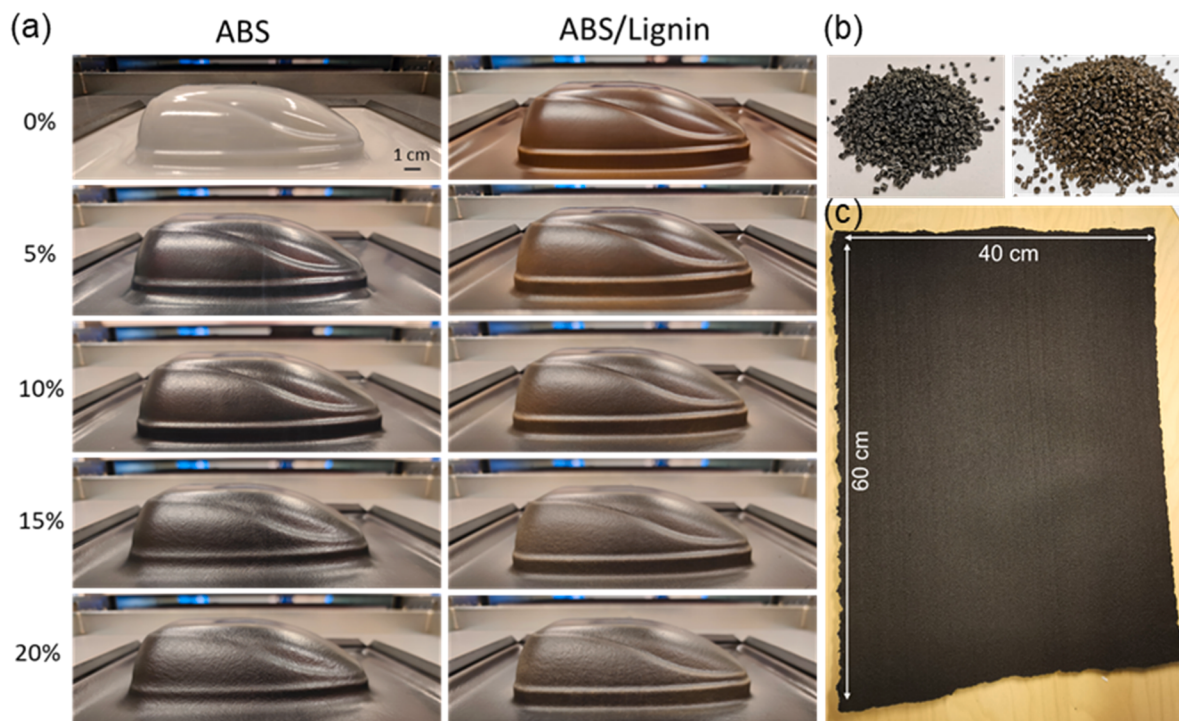


Fig. 4. Processability of the biocomposites: (a) Vacuum-formed ABS and ABS/lignin samples with different content of biochar and (b,c) Scale-up production of the biocomposites. b) shows the pellets of A10 (left) and AL10 (right) produced in an industrial scale extruder, and c) shows a piece of the extruded sheet of the AL10 sample.

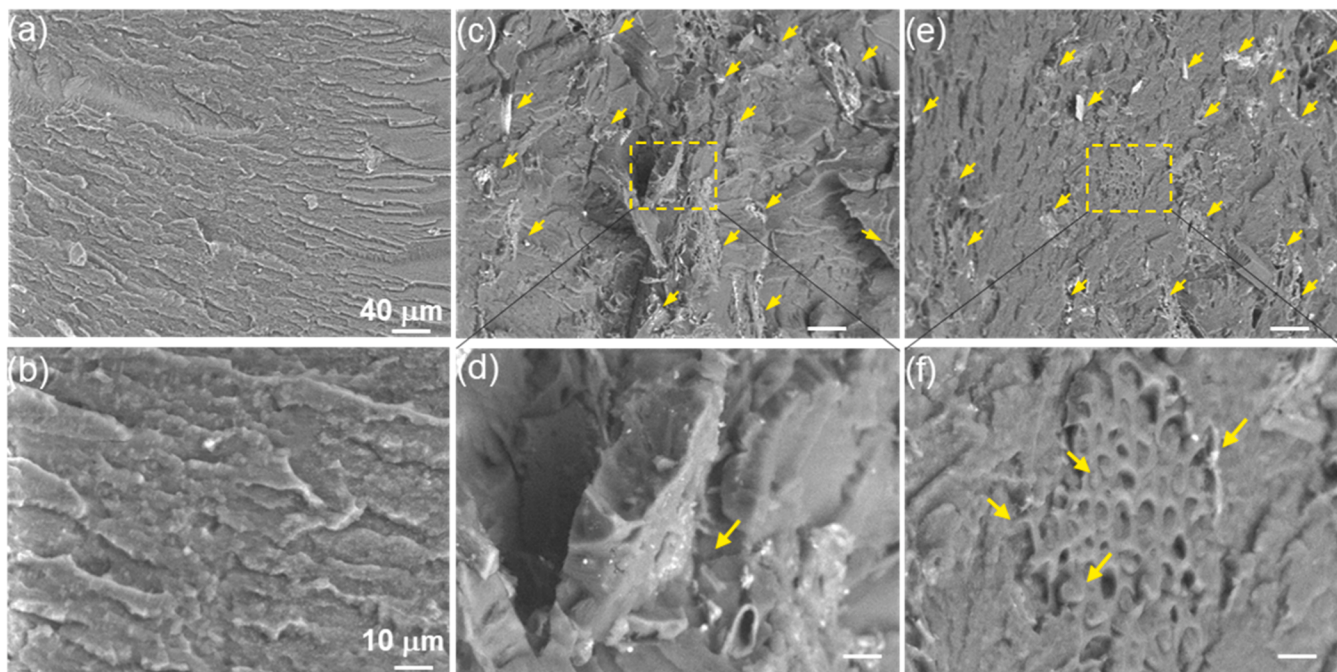


Fig. 5. SEM images of cryo-fractured surfaces of the ALO (a,b), A20 (c,d), and AL20 (e, f) samples. Arrows in c and e show the even dispersion of biochar particles and arrows in f highlight good cohesion and infiltration. The scale bar length is 40 μm in all images of the first row and 10 μm in all images of the second row.

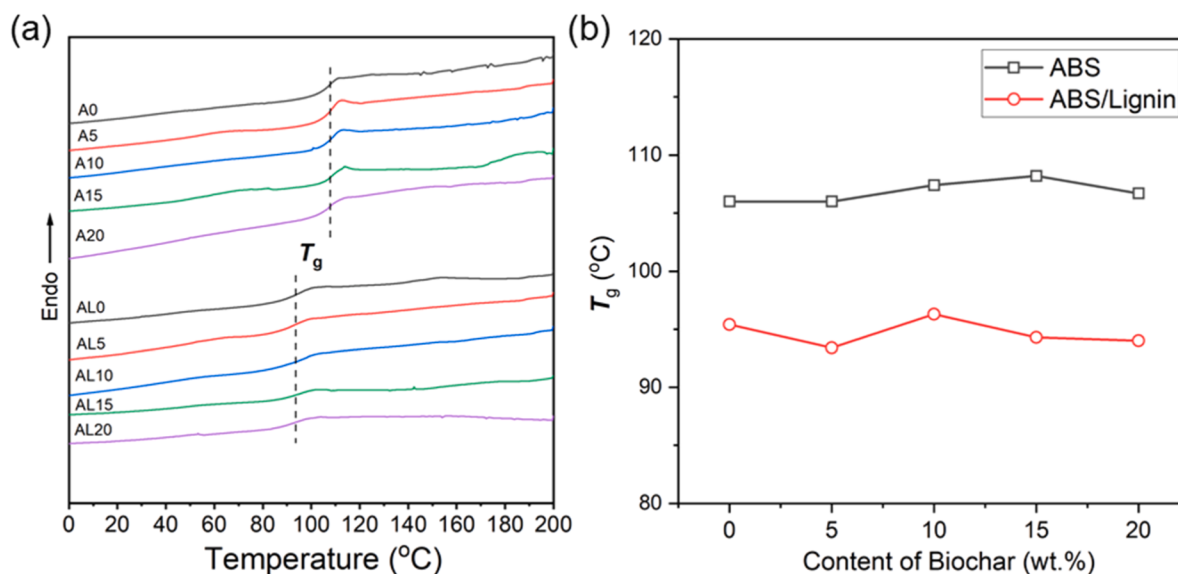


Fig. 6. (a) DSC heating curves (10 $^{\circ}\text{C}/\text{min}$) and (b) T_g of the samples with different content of biochar.

addition of lignin was observed in the DTG curves, with the peak temperature at 421 $^{\circ}\text{C}$ for the samples containing lignin and 430 $^{\circ}\text{C}$ for those without lignin (Fig. S3). The decomposition temperatures were independent of the biochar content for both ABS and ABS/lignin matrix materials (Fig. 7b). It should be noted that the commonly employed processing temperature for ABS typically ranges from 190 to 250 $^{\circ}\text{C}$, which is ca. 100 $^{\circ}\text{C}$ lower than the decomposition temperature of the ABS/lignin samples. Therefore, despite the reduction in thermal stability due to the incorporation of lignin, there is still a considerable safety margin above the processing temperature range for ABS/lignin samples. The preserved thermal stability at the processing temperature window for the lignin samples was also demonstrated by the above-mentioned successful processing trials, including compressing moulding, vacuum forming, melt-compounding, and sheet extrusion on both lab and

industrial scale. Moreover, the incorporation of lignin increased the amount of the char residues, from 1.2 % (A0) to 12.5 % (AL0) (Fig. 7c), which often leads to improved fire properties. This finding confirmed the high char-forming ability of lignin, which was attributed to the abundant aromatic structures present in it. In addition, the amount of char residues increased with increasing biochar (non-pyrolytic carbon) content for both ABS and ABS/lignin matrices; the A15 sample had 25 % of residues after burning.

3.5. Fire performance of the biocomposites

Fig. S4 shows the heat release rate (HRR) and total heat release (THR) curves, using cone calorimetry. HRR and THR determine the rate of fire development, whereas the peak of HRR (pHRR) indicates the

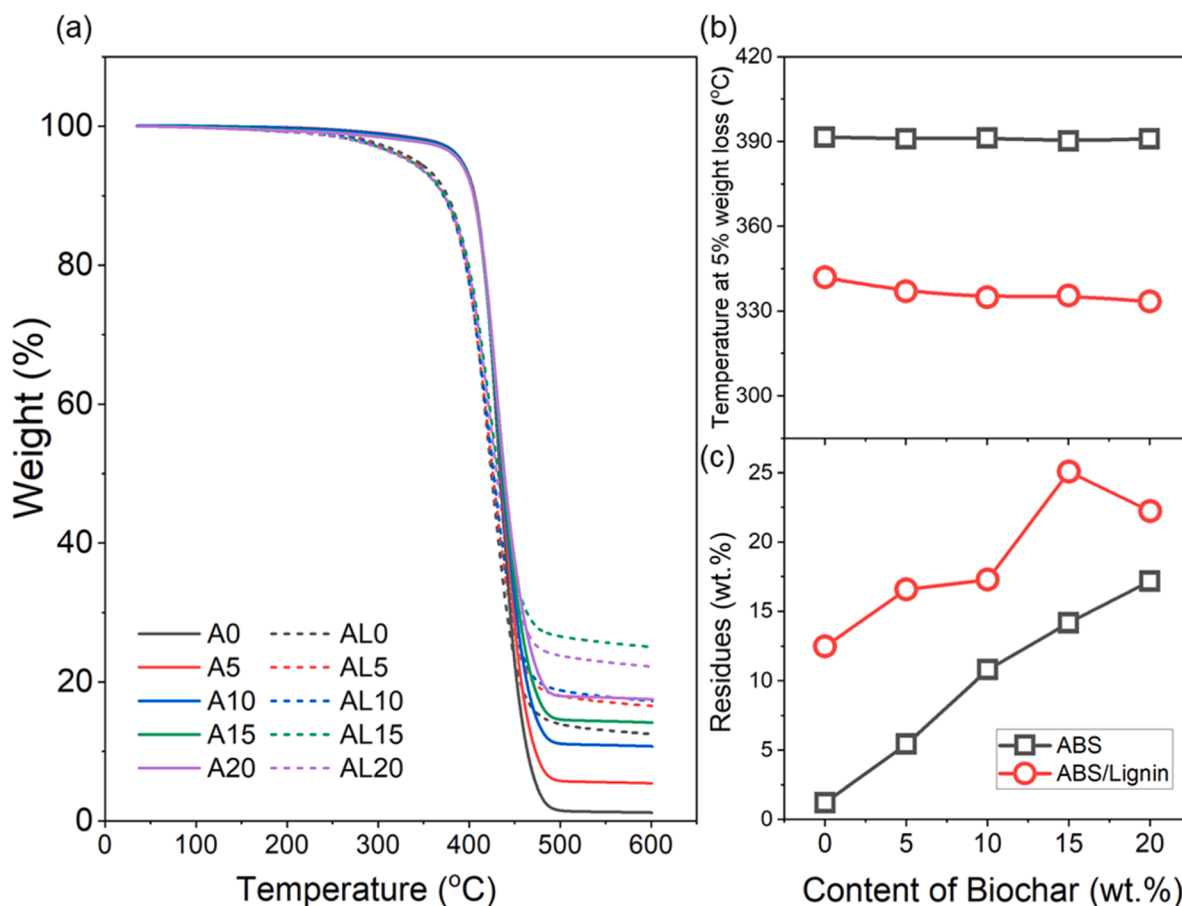


Fig. 7. (a) TG curves (solid and broken curves represent samples without and with lignin, respectively). (b) Decomposition temperature and (c) the amount of residues at 600 °C plotted as a function of biochar content.

intensity of the fire. Fig. 8 shows that the incorporation of 30 wt% lignin led to a decrease in pHRR and THR by 14 % from 1330 (A0) to 1148 kW/m² (AL0) and by 17 % from 55 to 45 MJ/m², respectively. The addition of biochar also reduced the pHRR, with a higher biochar content leading to a more significant decrease. At the highest biochar loading, the pHRR of the A20 sample decreased to 978 kW/m² (a 26 % change compared to the A0 sample). Similarly, ABS/lignin samples exhibited a decrease in pHRR with increasing biochar content, suggesting that biochar and lignin together effectively reduced the pHRR of the biocomposites. Remarkably, the AL20 sample exhibited a pHRR of 674 kW/m², only half (49 % reduction) of pure ABS (A0). This joint reduction of pHRR by biochar and lignin (49 %) even surpassed the sum of their individual decrease (40 % = 14 % + 26 %), indicating the synergistic effects of biochar and lignin in significantly reducing the pHRR (i.e., the intensity of the fire) of ABS materials.

The combined reduction in THR from lignin and biochar was also observed when the biochar content exceeded 10 wt%. Notably, at a 20 wt% biochar content, synergistic effects between biochar and lignin were evident, with a 32 % reduction in THR, which surpassed the sum of their individual effects, i.e., 23 % (17 % (lignin) + 6 % (biochar)). When the synergistic effects occurred between biochar and lignin, the total smoke production (TSP) (AL15 and AL20 samples) was much lower than that of the pure ABS sample (Fig. 8).

The fire performance index (FPI, the ratio of sample ignition time to pHRR) was utilized to evaluate the overall fire performance. A higher FPI indicated better fire performance. Fig. 8 shows that adding either biochar (up to 20 %) or lignin (30 %) alone slightly improved the fire performance of the ABS material. However, when biochar and lignin were combined, significant improvements in fire performance were observed at biochar contents exceeding 10 %. As a result, for ABS/

lignin/biochar biocomposites, there were substantial favorable changes in all four parameters presented in Fig. 8 when the biochar content increased from 10 to 15 wt%. The AL15 and AL20 samples lost weight much more slowly during the combustion and had more significant amounts of residues (after 200 s) than all the other samples (Fig. S5). This finding aligned with the TGA pyrolysis results, where the combination of biochar and lignin in the composite samples vastly increased the amount of residues.

The UL94 vertical burning tests were conducted to further evaluate the fire properties of the samples. Neat ABS and ABS with lignin exhibited significant dripping, which ignited the cotton indicator placed below. However, with the incorporation of biochar, this dripping phenomenon was significantly reduced. Notably, when the biochar content exceeded 15 %, the A15 and A20 samples exhibited no dripping and formed char during burning (Fig. 9a). Although the formed char for these samples occasionally broke apart and ignited the cotton indicator, more stable char (no breaking) was observed for the AL15 and AL20 samples (Fig. 9a). This stable char left the cotton indicator unignited. The height ratio of residual char to original sample was 40 %, 61 %, 98 %, and 100 % for A20, AL10, AL15, and AL20 samples, respectively. In contrast, the other samples exhibited no residual char, corresponding to a ratio of 0 %. While these improvements in fire properties were evident, none of the samples met the UL94 rating criteria, as their afterflame times exceeded 30 s, surpassing the upper limit (10 s for V-0, 30 s for V-1 and V-2), and their flames traveled up the hold clamp. A dense char layer was formed on the AL20 samples during the burning test (Fig. 9b-d), and the biochar particles were observed in the residual char (Fig. 9c and e).

The thermally stable biochar particles acted as a barrier, preventing fuel release and providing thermal insulation for the base polymer,

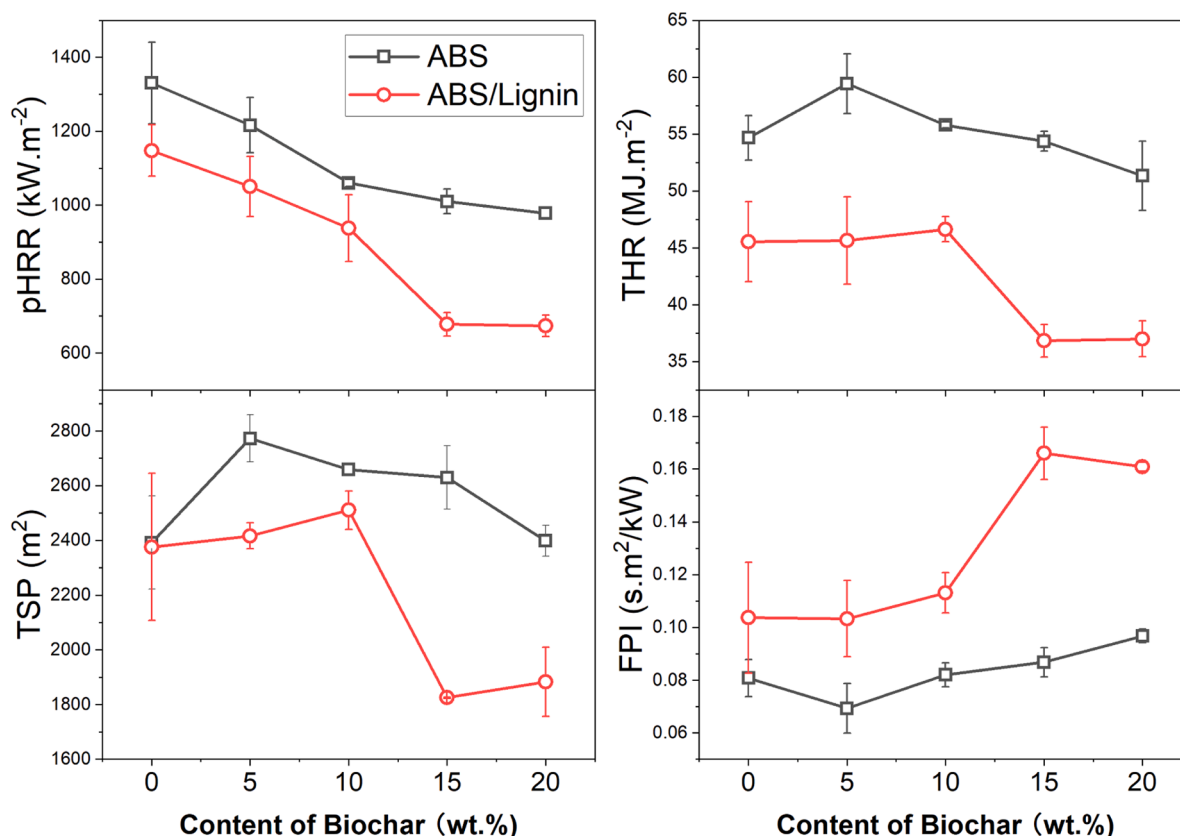


Fig. 8. Peak heat release rate (pHRR), total heat release (THR), total smoke production (TSP), and fire performance index (FPI), measured with the cone calorimeter.

thereby improving the flame-retardant properties of the biocomposites. However, as the dispersed phase in the ABS matrix, the char formed from the in-situ pyrolysis of lignin droplets was isolated from each other (as illustrated in Fig. 10). As a result, the transfer of heat, fuel, and oxygen through the areas among lignin droplets remained unaffected. When the blend contained 30 wt% lignin, only ca. 30 % of the cross-section was covered by lignin, with the remaining portion being the continuous matrix phase. This limitation accounted for the moderate improvement in fire performance achieved by lignin in the biocomposites. A similar limitation was applied to biochar when low levels of biochar were used. When lignin and biochar were added together, the hypothesis is that biochar particles filled the gaps among lignin droplets, effectively increasing the size of the barrier area in combination with lignin char (Fig. 10). Note that the high porosity of biochar allowed for a much larger volume fraction in the biocomposites compared to its mass fraction. At high biochar content, the biochar particles were close enough to form a robust char barrier layer or network in conjunction with lignin biochar, as revealed in Fig. 9c. The above findings suggested that such a char layer/network was formed in the ABS/lignin/biochar material at a biochar content between 10 wt% and 15 wt%. This protective char layer/network could impede heat transfer and limit the fuel release between the ABS and the heat source, thereby contributing to the synergistic effect of biochar and lignin in enhancing the fire performance of ABS materials. Moreover, in areas where the barrier layer was not fully covering, the presence of a high amount of the bio-components (lignin and biochar) disrupted the direct transfer path of heat, oxygen, and fuel. This disruption increased the length of the transfer path, consequently improving the fire performance.

3.6. Water uptake

Fig. 11a shows that the water uptake increased rapidly in the early stage of submersion and then leveled off or increased more slowly after

ca. 8 days. The addition of lignin slightly increased the water uptake (less than 1 wt%, Fig. 11b) due to the presence of hydrophilic functional groups such as hydroxyl, methoxyl, carbonyl, and carboxyl in lignin. Besides, the water uptake increased with increasing biochar content for both ABS and ABS/lignin matrices. As a highly porous material, the biochar samples sorbed up to 80 % of their own weight (Gray et al., 2014). In the composites, the ABS matrix filled many of the micropores in the biochar (see Fig. 5 e), and the porosity of biochar could be significantly reduced during the sample preparation process because of the high pressure in the compression moulding. As a result, the addition of biochar only slightly increased the water uptake. For instance, at a 20 wt% biochar content (AL20), the water uptake after 30 days was 3.1 wt%, which was 1.4 wt% greater than that of the biochar-free AL0 sample (1.7 wt%).

Note that the submersion of the samples in water represents the most severe condition. In many applications, such as in automobiles, ABS components are rarely exposed to liquid water for extended periods, and several products are used in the interior. Therefore, the overall effect of water uptake on the properties of the biocomposites under typical usage conditions (relative humidity lower than 100 %) would be less significant. Furthermore, the water absorption is considerably lower than that of polyamides, which are also commonly used in vehicles. For example, polyamide 6 can absorb up to 10 % water when fully immersed (Lei et al., 2021).

3.7. Mechanical properties

The Young's modulus increased with rising biochar content in both neat ABS and ABS/lignin matrices, indicating a stiffening effect of biochar particles (Fig. 12b). This stiffening effect has also been observed when used in other polymer materials, such as polypropylene (Das et al., 2016) and poly(lactic acid) (Aup-Ngoen and Noipitak, 2020). At each biochar content level, ABS/lignin composites exhibited a ca. 150 MPa

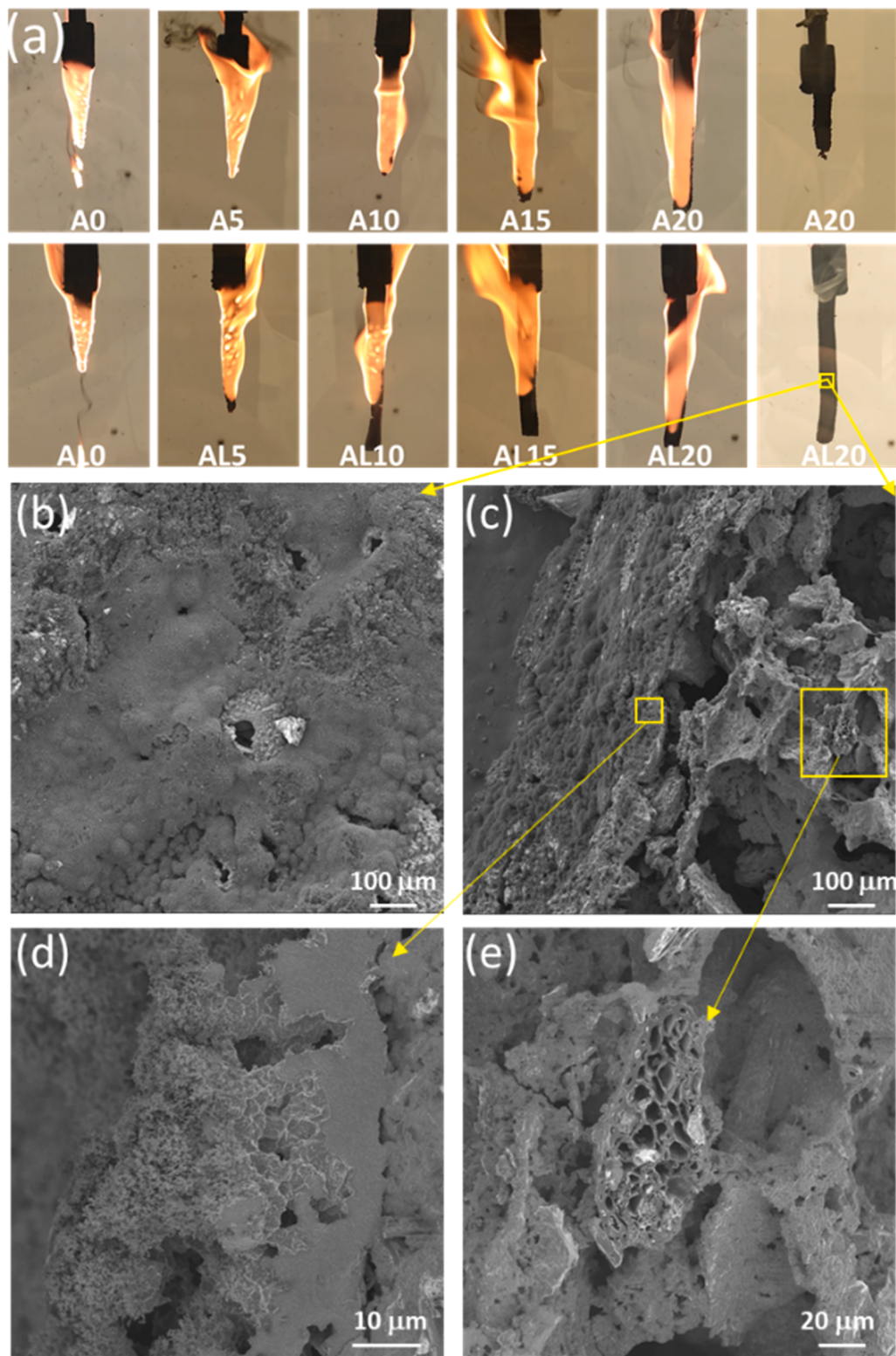


Fig. 9. UL94 vertical burning tests: (a) Sample images after 40 s afterflame time, the two images to the right show the residual char formed after the burning test for the A20 and AL20 samples, respectively; (b) SEM surface view of AL20 residual char; (c-e) SEM cross-sections of AL20 residual char.

higher Young's modulus than ABS without lignin. The combined stiffening effects of biochar and lignin resulted in a 32 % increase in Young's modulus, from 1250 MPa (A0) to 1654 MPa (AL20) (Fig. 12b). However, the incorporation of fillers led to a 23 % reduction in tensile strength, decreasing from 31 MPa (A0) to 24 MPa (AL20) (Fig. 12c). Notably, the maximum tensile stress was used here as the tensile

strength, as the composite samples fractured before yielding (Fig. 12a), leading to lower values than that of neat ABS, which broke after yielding. Despite the reduced maximum stress, the composites exhibited higher stress at a strain before fracturing compared to pure ABS (Fig. 12a), indicating a reinforcing effect from these two fillers. The biocomposites fractured before substantial yielding (at ~3 % strain)

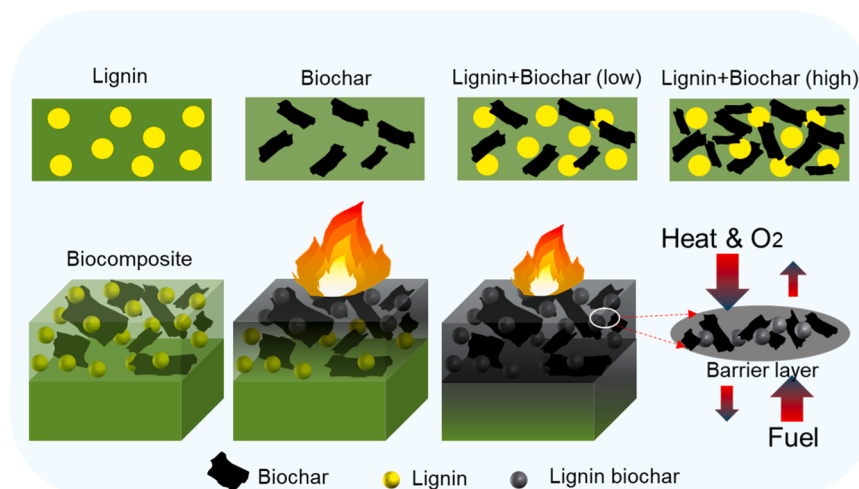


Fig. 10. Schematic diagram of the morphology of the blends with lignin alone, biochar alone, and lignin combined with low or high content of biochar, and the proposed burning process of the ABS/lignin/biochar biocomposites.

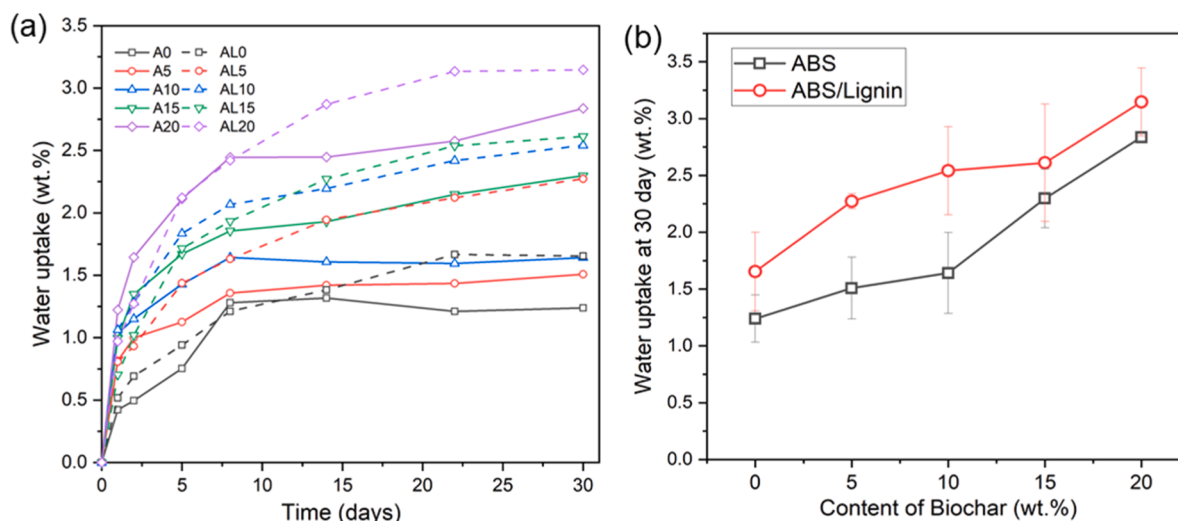


Fig. 11. (a) Water uptake curves of the samples submerged in water at room temperature and (b) their water uptake after 30 days of immersion.

(Fig. 12a), resulting in a significantly lower strain at break (<3 %) compared to pure ABS (9 %) (Fig. 12d).

3.8. Carbon footprint

The production of lignin and biochar releases 870 g CO₂e/kg and 365 g CO₂e/kg, respectively, which is significantly lower than that of ABS (4 540 g CO₂e/kg) (Table S1). As a result, incorporating these bio-based materials and consequentially replacing part of the ABS can substantially reduce greenhouse gas (GHG) emissions during production, per kg of final material. In addition, the use of bio-based materials lowers the proportion of fossil carbon in the polymer composites, leading to further GHG reductions during the end-of-life combustion. Consequently, total emission reductions increased with higher biochar content, with 20 % biochar in ABS (A20 sample) achieving a 19 % reduction in emissions (Fig. 13). Similarly, adding 30 % lignin (AL0 sample) resulted in a 27 % decrease in GHG emissions.

When both fillers were combined, emission reductions were even more pronounced, reaching approximately 40 % for the AL20 sample (Fig. 13). The material production stage of these biocomposite samples contributed with 54–58 % of the total emission reductions, slightly exceeding the reductions achieved during the end-of-life combustion.

3.9. Overall evaluation

The overall performance of the studied biocomposites is evaluated as a radar plot (Fig. 14). Here, the neat matrices A0 and AL0, along with their highest biochar version A20 and AL20, are evaluated based on important performance parameters assessed in this article. There are improvements in certain areas, while there are tradeoffs in others. The improved fire performance, higher modulus, and reduced greenhouse gas emissions are at the cost of higher water uptake, lower strain at break and lower thermal stability. However, as it is possible to choose the amount of bio-based content that would be acceptable to use and still retain adequate properties, the fact that all biocomposites presented in this article retained sufficient processability speaks volumes for the future uses of the herein evaluated materials.

4. Conclusions

The ABS/lignin/biochar materials demonstrated several favorable attributes, including a high bio-based content (up to 44 %), good processability, and improved fire performance. The high bio-based content and retained good processability are essential to meet their application's quality demands while utilizing more sustainably acquired materials to

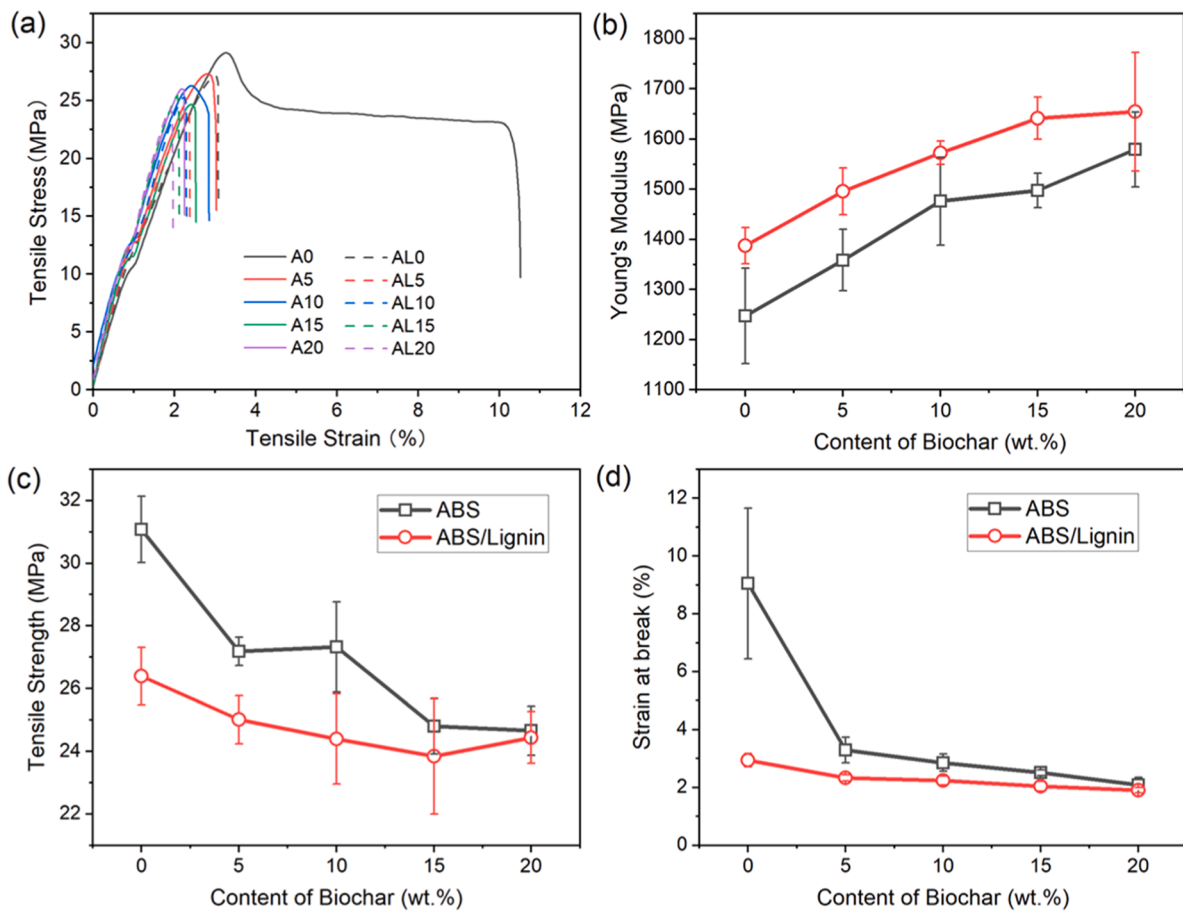


Fig. 12. (a) Tensile stress-strain curves, (b) Young's modulus, (c) tensile strength, and (d) strain at break of the samples.

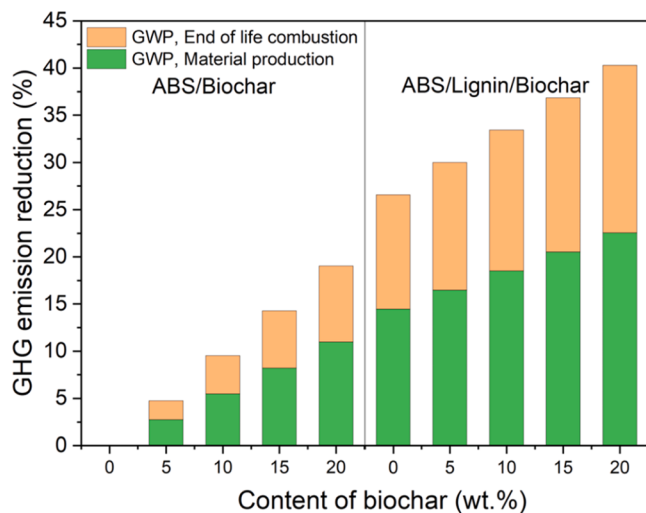


Fig. 13. Greenhouse gas (GHG) emission reductions related to material production and their end-of-life fossil carbon release.

reduce greenhouse gas emissions (up to 40 %). Although their thermal stability was somewhat decreased, they remained suitable for high-temperature processing required in extrusion, injection moulding, and vacuum forming and exhibited acceptable resistance to water. Adding to this, the findings that all biocomposites show improved fire performance, significantly better than that of neat ABS, further complement the suitability of these biocomposites in their target application. This effect stemmed from a formed protective char layer, which reduces heat

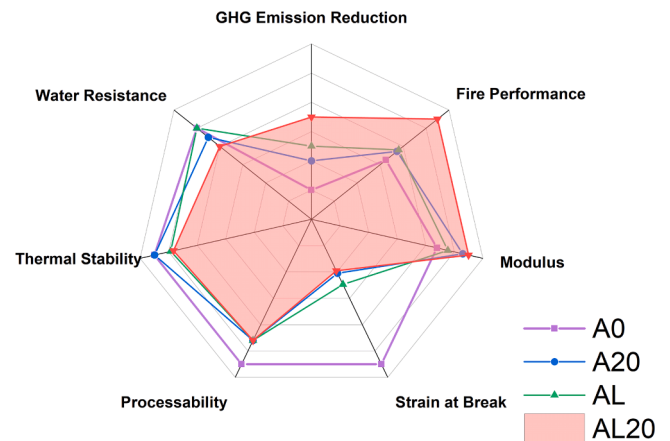


Fig. 14. Radar plots comparing the performance and bio-based content of neat ABS (A0) and the blends A20, AL0, and AL20.

transfer and disrupts paths for transferring oxygen and fuel to the heat source. A more complete barrier would, however be required to obtain a UL94 rating. Further, in terms of mechanical properties, the increase in the stiffness of the material with higher bio-based content also came with a tradeoff in other mechanical properties such as the strain at break. One area, in particular, that requires improvement in future work is their ductility (and hence toughness) to further enhance their overall performance and widen their potential applications. In applications where ductility and toughness are secondary, and good fire performance along with more sustainable sourcing of raw materials is desired, the

biocomposites could still be a good choice. This shows the potential for using biocomposites of ABS with lignin and biochar for applications in the automotive industry.

CRedit authorship contribution statement

Anna Matsson: Writing – review & editing. **Daniel Helgesson:** Funding acquisition. **Oisik Das:** Writing – review & editing. **Andreas Åhrlin:** Writing – review & editing, Project administration. **Thomas Roulin:** Writing – review & editing. **Yunus Can Görür:** Writing – review & editing. **Christopher Carrick:** Writing – review & editing, Conceptualization. **Thomas Prade:** Writing – original draft, Investigation. **Xin-Feng Wei:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Rhoda Afriyie Mensah:** Writing – review & editing, Investigation. **Anton Bjurström:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Lars Jerpdal:** Writing – review & editing, Conceptualization. **Hedenqvist Mikael:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Stefan Bruder:** Writing – review & editing.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.indcrop.2025.121402](https://doi.org/10.1016/j.indcrop.2025.121402).

Data availability

Data will be made available on request.

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