




Reducing formaldehyde emissions and enhancing performance of particleboards through the incorporation of activated carbon produced from Scots pine wood residues

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Abstract: Wood-based composite boards present a problem due to formaldehyde emissions from engineered particleboard, which pose health and environmental risks. This study explored the production of activated carbon (AC) from Scots pine (*Pinus sylvestris*) wood residues using phosphoric acid (H_3PO_4) as a chemical activator. The process of using waste biomass as raw material for AC production improves waste management and contributes to the circular economy by creating a high-value product from forestry industry byproducts. Activated carbon with a Brunauer–Emmett–Teller (BET) surface area of $1066.46\text{ m}^2\text{-g}^{-1}$ and a porous structure that enhances adsorption capacity was incorporated into urea-formaldehyde (UF) resin at varying levels (0.0%, 0.5%, 1.0%, and 1.5% by dry weight of the adhesive) for particleboard production. These boards were evaluated for their formaldehyde emissions, physical properties, and mechanical properties. Results showed that adding AC reduced formaldehyde emissions significantly, by up to 50%. The particleboards prepared using the modified resin also demonstrated improved physical and mechanical properties, with a 10% increase in density contributing to enhanced strength and durability. Overall, this approach shows the potential to reduce formaldehyde emissions and improve the sustainability of particleboard production, improving both environmental and human health

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Key words: activated carbon; wood residue; formaldehyde emissions; particleboard

Introduction

In recent years, environmental sustainability and resource efficiency have become increasingly important in industrial applications, particularly in the wood-based composite industry. Particleboard, a popular furniture and building material, is typically made with urea-formaldehyde (UF) resin as a binder due to its strong adhesive characteristics and low cost. However, because formaldehyde is a known carcinogen, the emissions from these boards represent a significant health risk and an environmental problem.¹ Several methods have been tried to decrease formaldehyde emissions from wood-based boards such as microencapsulation of formaldehyde scavenging agents,² modifying the adhesive, adding urea, treating board surfaces, and using alternative binders and raw materials³ such as pinecone⁴ and activated carbon (AC).⁵

The addition of AC to UF resin is one approach that shows promise. Outstanding adsorption capabilities are displayed by AC, which is well known for its large surface area, porosity, and surface functional groups. Integrating AC into particleboards can reduce formaldehyde emissions due to its adsorption capabilities and improve the physical and mechanical properties of the boards.⁶ This dual benefit of reducing harmful emissions while enhancing the material's performance suggests that AC could be an attractive additive in particleboard production.

Chemical activators such as sodium hydroxide,⁷ potassium hydroxide,⁸ potassium carbonate,⁹ and phosphoric acid¹⁰ are employed commonly in the production of AC. Phosphoric acid (H_3PO_4) is a widely utilized chemical activator, as it does not result in the formation of undesirable impurities in AC following the activation process. It is also a vital chemical activator in the production of AC due to its ability to catalyze the formation of a porous structure, control pore size distribution, and maintain chemical stability.¹¹

The choice of raw material is another critical factor in producing AC. The use of agricultural residues, industrial byproducts, and other waste biomass in AC production addresses waste management challenges and adds value to otherwise discarded materials. Common waste materials employed in the production of AC include coconut shells, sawdust, rice husks, fruit stones, and various types of agricultural residues. These materials are chosen for their

high carbon content, availability, and low cost.¹² Scots pine wood residues, a byproduct of the timber industry, are a viable and sustainable source of carbon material.^{13,14} Converting these residues into AC reduces waste and generates a high-value product.¹⁵

This study aimed to explore the benefits of adding activated carbon to particleboard through a comprehensive evaluation of the product. It focused on producing AC from Scots pine wood residues using H_3PO_4 and the chemical activation method, incorporating the AC into UF resin and assessing the mechanical and physical properties of these particleboards as well as formaldehyde emissions. This approach can improve the product's performance by increasing the mechanical and physical qualities of particleboards as well as meeting environmental and health safety standards by reducing formaldehyde emissions significantly.

Materials and methods

Materials

Particleboard is an engineered wood product made from wood chips, sawmill shavings, or sawdust, which are bonded together using resin or another adhesive and then pressed into sheets under heat and pressure. A mixture of wood chips derived from *Pinus nigra*, *Populus nigra*, *Carpinus betulus*, and *Fagus orientalis* was utilized in the production of particleboard and provided from wood based composite production factory (Kastamonu, Turkey). The UF adhesive had a viscosity of 260–310 mPa·s, a density of 1270–1290 $\text{kg}\cdot\text{m}^{-3}$, and a solids content of $65\% \pm 1.0$ (Kastamonu, Turkey). All measurements were taken at 23 °C. A 20% ammonium chloride (NH_4Cl) solution (Merck, Darmstadt, Germany) was used with the dry weight of adhesive at a weight ratio of 1.0% for curing. Scots pine is widely used in the furniture and timber industries, with production residues typically disposed of by burning. To increase their added value, alternative uses beyond combustion were sought. Scots pine waste wood was provided by a woodworking factory (Seydişehir, Turkey). The formaldehyde concentration was measured using the Merck (Darmstadt, Germany) Spectroquant test kit. Fluka (Buch, Switzerland) and Merck provided analytical purity chemicals for this investigation.

Methods

Production of Scots pine-based activated carbon

First, 600 g of Scots pine wood residues was stirred with 600 mL of H_3PO_4 (concentration of phosphoric acid is 50% weight/weight) (Fluka, Buch, Switzerland) and 600 mL of water. The mixture was subjected to a temperature of 105 °C for 120 min to facilitate the interaction between Scots pine wood residues and H_3PO_4 . It was then dried for 1 day at 85 °C in an oven (Nuve, Ankara, Turkey). The desiccated Scots pine underwent pyrolysis by being subjected to a flow of nitrogen gas ($55 \text{ mL}\cdot\text{min}^{-1}$) at a temperature of 600 °C for 90 min (square series, Nevola, Ankara, Turkey) and subsequently cooled to 23 °C. The AC produced was cleansed initially using a potassium hydroxide (KOH) (Fluka, Buch, Switzerland) solution at a concentration of $0.5 \text{ mol}\cdot\text{L}^{-1}$ and cleaned again with hot deionized water until it reached a neutral pH. After drying the AC for 12 h at 85 °C, it was ground and made ready for use.

Production of particleboards

Three-layer particleboard samples were prepared using wood chips, with the composition distributed as follows: 20% for the top layer, 20% for the bottom layer, and 60% for the core layer, based on the total weight of the wood chips used. Chips, dried until they had a moisture content of between 1% and 3% were mixed, comprising 10% surface chips and 8% coarse chips by weight. These were bonded using urea-formaldehyde adhesive modified with 0.0%, 0.5%, 1.0%, or 1.5% AC, based on the dry weight of the adhesive. The gluing process was performed using an adhesive gun. The glued chips were then placed into a $400 \times 400 \times 300 \text{ mm}$ mold and subjected to cold pressing. The particleboard mat was then placed in a press heated to 180 °C, and pressed for 4 min (Cemil Usta, Ankara, Turkey). The process of forming particleboard sheets from the $400 \times 400 \times 300 \text{ mm}$ cube involves applying pressure and controlling the thickness using spacers. First, the material is compressed under a specific pressure of $2\text{--}4 \text{ Nmm}^{-2}$ to ensure proper bonding and density distribution. This pressure helps to consolidate the wood particles and resin into a uniform and stable board. To achieve the desired 16 mm thickness, thickness spacers (calibrated bars or stops) are used during the pressing process. These spacers control the final thickness by ensuring that the press stops at the required level, preventing over-compression or uneven surfaces. By using this method, the larger material cube is compressed and formed into uniform 16 mm thick sheets, making them suitable for further processing or application. The manufactured boards are designed to have a target density of $650 \text{ kg}\cdot\text{m}^{-3}$ and a

thickness of 16 mm. The boards had to be conditioned after being removed from the press. This included cooling them and placing them in an environment with a relative humidity of $65 \pm 5\%$ and a temperature of 20 ± 2 °C. Figure 1 shows the production scheme of the manufactured particleboard.

Characterization

The structural characteristics of these sample sheets – Brunauer–Emmett–Teller (BET) surface area and micro-pore volume – were evaluated using nitrogen adsorption–desorption isotherms with a Quantachrome Autosorb IQ BET analyzer (Quantachrome Corporation, Graz, Austria). X-ray diffraction patterns between 10° and 70° were analyzed using the SmartLab model X-ray device, (Rigaku, Tokyo, Japan). Before the experiments, AC was degassed for 3 h at 120 °C. Raman spectra (inVia RA 802, Renishaw, Wotton-under-Edge, United Kingdom) were obtained from 1000 to 2000 cm^{-1} with a single monochromatic light source. The microstructure of the AC was investigated using the Tescan, Maia3 Xmu type scanning electron microscope (SEM) (Maia3 Xmu, Tescan, Brno, Czech Republic) where the energy of the electrons used for imaging was set to 20.0 kV. The use of a gold coating increased the conductivity. An oxygen-filled atmosphere was used to conduct proximate analysis on a 2–3 mg sample using the Hitachi STA 7300 TG-DTG analyzer (Hitachi High-Tech Corporation, Hitachinaka, Japan). In their proximate analysis, Cai *et al.* (2017) used thermogravimetric analysis (TGA).¹⁶ The parameters in their equations were used to determine moisture (M) (Eqn 1), volatile matter (VM) (Eqn 2), ash (A) (Eqn 3), and fixed carbon (FC) (Eqn 4):

$$M = \frac{W - B}{W} \quad (1)$$

where W was the initial weight of the sample and B was the weight of the sample after drying;

$$VM = \frac{B - C}{W} \quad (2)$$

where W was the initial weight of the sample, B was the weight of the sample after drying, and C was the weight of the sample after devolatilization.

$$A = \frac{D}{W} \quad (3)$$

where W was the initial weight of the sample and D was the weight of the ash residue after complete combustion of the sample.

$$FC = 1 - (M + A + VM) \quad (4)$$

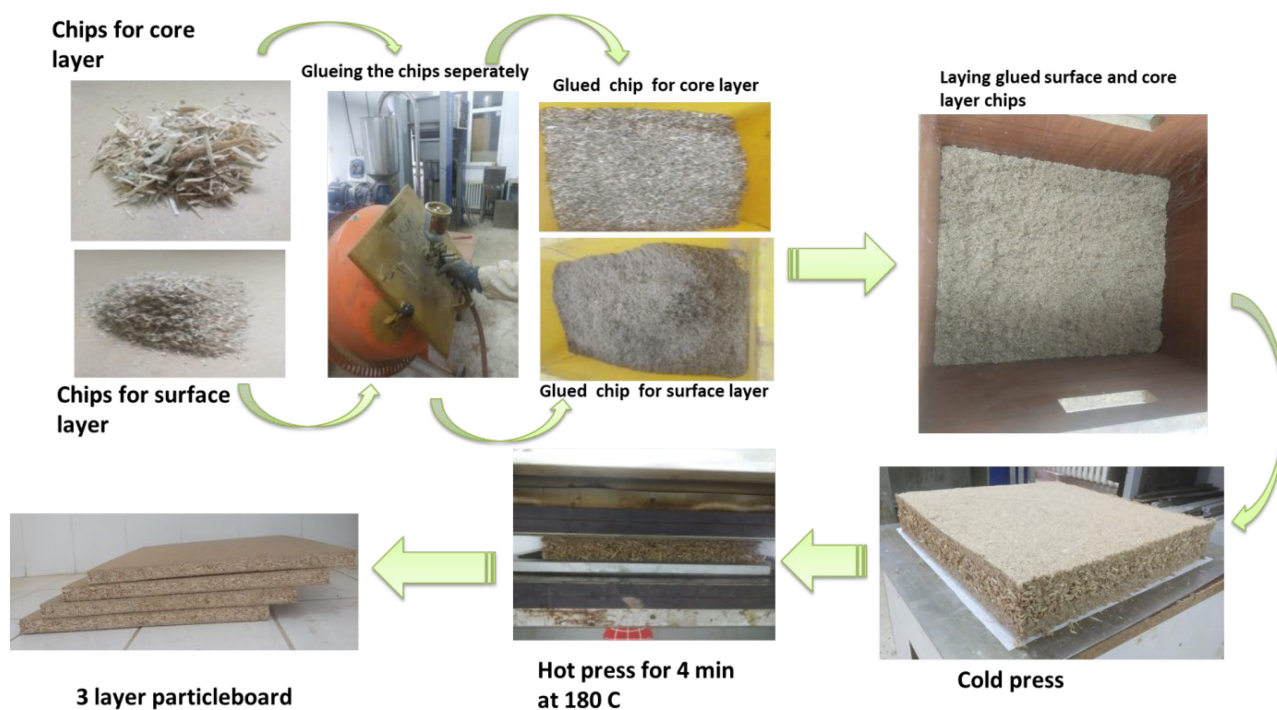


Figure 1. The production scheme of the manufactured particleboard.

The NC Technologies-ECS-8020 model elemental analyzer (NC Technologies, Milan, Italy) was used to conduct the elemental analysis. Total carbon (C), nitrogen (N), oxygen (O), and hydrogen (H) concentrations were measured in 5 mg oven-dried samples. After deducting the mass fractions of C, N, O, and H from the samples' total mass, the ash mass fraction was calculated.

The formaldehyde content, and mechanical and physical properties of the particleboards were examined to ensure that they met the specified requirements. The particleboard properties were evaluated in accordance with TS EN 312 (2012), the Turkish implementation of the European Standard EN 312, which specifies performance requirements for particleboards used in dry, humid, and structural conditions. The moisture content was determined following the TS EN 322 (1999) standard, which outlines the method for determining the moisture content of wood-based panels. The density of the particleboards was measured in accordance with TS EN 323 (1999), a Turkish standard for determining the density of wood-based panels. To evaluate the thickness swelling after immersion in water, the procedures outlined in the Turkish standard TS EN 317 (1999) were followed. Finally, the modulus of elasticity in bending and the bending strength of the particleboards were determined according to TS EN 310 (1999), which relates to the modulus of elasticity in bending and bending strength of the boards.

Further mechanical properties, such as the tensile strength perpendicular to the plane of the board, were determined using the TS EN 319 (1999) standard. Sampling, cutting, and inspection procedures were carried out following TS EN 326-1 (1999), which specifies the methods for sampling test pieces and expressing test results. The formaldehyde release from the particleboards was assessed using the extraction method specified in standard TS EN ISO 12460-2:2024,¹⁷ known as the perforator method. This method is crucial for evaluating the formaldehyde emission levels to ensure safety and compliance with health standards. The overall properties of the particleboard were tested in accordance with standard ASTM D1037 (2006),¹⁸ which provides test methods for evaluating these materials. Both mechanical and physical parameters were statistically examined using a one-way analysis of variance (ANOVA) with a 95% confidence level. Homogeneous groups with statistically significant differences ($P < 0.05$) were identified using the Duncan test.

Results and discussion

Properties of AC

The characteristics of AC produced from Scots pine wood residues with the chemical activator H_3PO_4 were determined before it was used in particleboard production. Figure 2 provides the nitrogen gas adsorption–desorption isotherm

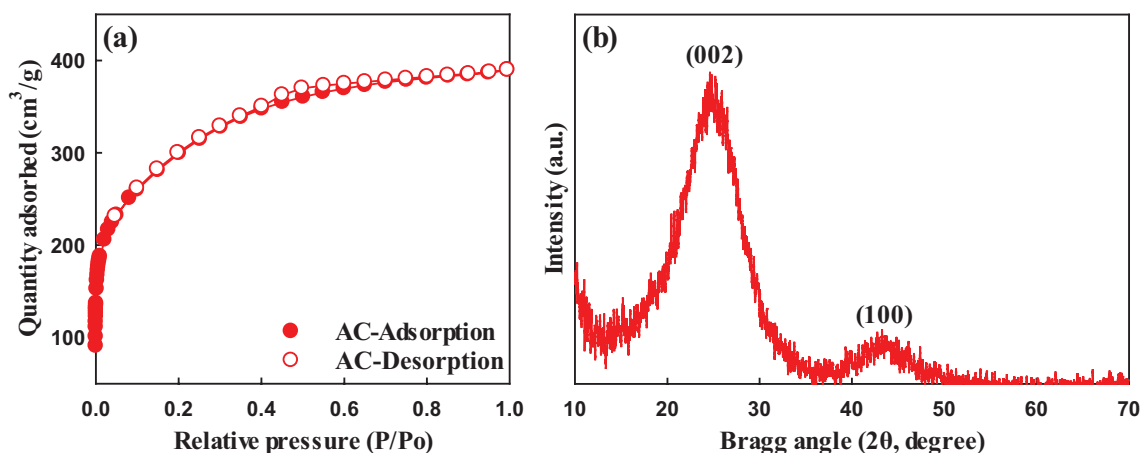


Figure 2. The nitrogen gas adsorption–desorption isotherm (a) and X-ray diffraction (XRD) (b) images of activated carbon (AC).

for the AC and the X-ray diffraction (XRD) image of Bragg angle intensity.

The nitrogen gas adsorption–desorption isotherms of the AC were studied at 77 K, revealing a Type I(c) isotherm, indicative of the presence of a considerable number of mesopores and well developed micropores, as illustrated in Fig. 2(a). Nonetheless, the presence of an H4-type desorption hysteresis loop in the relative pressure (P/P_0) range of 0.45–0.90 confirms capillary condensation of nitrogen in the mesopores at subsaturation pressures.¹⁹

Bragg angle intensity refers to the diffraction intensity of X-rays or neutrons at specific angles, providing information on the crystal structure, phase composition, and atomic arrangement of a material. Sharp diffraction peaks are observed in crystalline structure; broader and lower intensity patterns are formed in amorphous or porous structure in materials.²⁰ Activated carbon is an amorphous material with an irregular structure. It therefore shows broad diffraction peaks instead of sharp peaks in XRD measurements. The width and intensity of the peaks are used to understand the degree of graphitization of activated carbon and the irregularity in its structure.²¹ The crystal structure of AC was investigated using XRD. The XRD pattern in Fig. 2(b) showed distinct peaks at 2θ angles of 23.90° and 42.05° , which correspond to the (002) and (100) crystallographic planes, respectively. The strong peak at 23.90° was ascribed to residual cellulose crystallites, showing that the original biomass structure was partially retained.²² This property has also been discovered in AC produced from biological waste, indicating a common structural trait in similar materials.^{23,24} The existence of these peaks reveals the graphitic and amorphous character of the AC, which might affect its adsorption capabilities and overall effectiveness

in practical applications. The complete breakdown of the cellulose crystallites in their first stages did not include the interaction of H_3PO_4 with lignocellulosic substances. Instead, it indicated that the cellulose underwent a conversion into smaller fragmented structures that maintained the primary crystalline shape but with altered dimensions, and displayed sharp peaks as shown in the XRD results.²⁵ The diffraction profiles at $2\theta = 42.05^\circ$ exhibited a broad pattern, and the peaks had decreased intensity. This was attributed to the reduced growth of intergraphitic layers.²⁶ During chemical activation using H_3PO_4 , the activator induced the cleavage of ether bonds in lignocellulosic raw materials, resulting in the formation of smaller molecular components.²⁷ The observed diffraction patterns were linked to the presence of deteriorated cellulose, disorganized graphene layers, and newly formed polymeric layers.

Table 1 summarizes the pore properties of the AC. The specific surface area (S_{BET}), micropore volume (V_m), mesopore volume (V_M), and total pore volume (V_T), and average pore diameter (D_p) are essential for determining the adsorption capacity and effectiveness of the AC.

The BET surface area of the AC was $1066.46 \text{ m}^2 \cdot \text{g}^{-1}$. This is in line with other studies that reported surface areas of $1000\text{--}1200 \text{ m}^2 \cdot \text{g}^{-1}$ for ACs produced using H_3PO_4 activation.²⁸ With a micropore volume of $0.426 \text{ cm}^3 \cdot \text{g}^{-1}$ and a mesopore volume of $0.177 \text{ cm}^3 \cdot \text{g}^{-1}$, the total pore volume was $0.603 \text{ cm}^3 \cdot \text{g}^{-1}$. This indicates a significant proportion of micropores, which are crucial for high adsorption capacity. The average pore diameter was 1.56 nm, indicating the presence of both micropores and mesopores, which are suitable for diverse adsorption applications. This is consistent with the pore diameters found in the AC from rubber wood sawdust, which had average pore diameters ranging from 1.5 to 2 nm.²⁹ The

Table 1. Pore properties, proximate analysis, and ultimate analysis of activated carbon (AC).

Pore properties		Proximate analysis (%)	
S_{BET} (m^2g^{-1})	1066.46	Moisture	4.23
V_{m} (cm^3g^{-1})	0.426	Volatile matter	25.63
V_{M} (cm^3g^{-1})	0.177	Ash	5.91
V_{T} (cm^3g^{-1})	0.603	Fixed carbon	64.23
V_{m} (%)	70.35	Ultimate analysis (%)	
V_{M} (%)	29.35	C	65.8
D_{p} (nm)	1.56	H	3.0
Yield (%)	35.91	N	5.6
		O	25.6

Abbreviations: D_{p} , average pore diameter; S_{BET} , The specific surface area; V_{M} (%), percentage of mezopore volume; V_{m} (%), percentage of micropore volume; V_{M} , mezopore volume; V_{m} , micropore volume; V_{T} , total pore volume.

yield of the AC was 35.91%. Various other studies show that the yield of AC formed at 600 °C when activated with H_3PO_4 ranged between 25.2% and 38.0%.^{30,31}

Raman spectroscopy is a technique that has shown to be quite successful in the characterization of materials. The Raman spectroscopically sensitive covalent bonds are those that are very symmetrical and have little to no inherent dipole moment. The carbon–carbon bonds of these materials satisfy this requirement completely, which makes Raman spectroscopy very sensitive to them and provides important structural information. Figure 3 shows the AC Raman spectra.

The Raman spectra of the AC show two bands at around 1592 and 1325 cm^{-1} , indicating that the produced AC had a structure similar to graphite. These bands are called the G (graphite) and D (disorder) bands. These structures are used to describe the various structural forms of carbon. Sp^2 -bonded carbon and E2g resonance oscillation give rise to G peaks, and the graphite structure's boundaries are often represented by D bands. Heteroatoms, C=C bonds, sp^2 – sp^3 carbon bonds, edge effects, E2g disorder, and volatile components are the main causes of the D band's formation.³² The Raman spectrum is known to be dependent primarily on the sp^2 and sp^3 fraction ordering, which is directly connected to the pyrolysis conditions.³³ The structure and level of graphitization in the ACs are indicated by the density ratio ($I_{\text{D}}/I_{\text{G}}$). In this study, the $I_{\text{D}}/I_{\text{G}}$ ratio of the AC was calculated to be 1.14. This relatively high ratio indicates that AC has less aromatic ring structure and more carbon-containing defects leading to the formation of oxygenated functional groups on its surface.³⁴

Figure 4 presents SEM images of the AC at different magnifications ($\times 250$ and $\times 200\,000$).

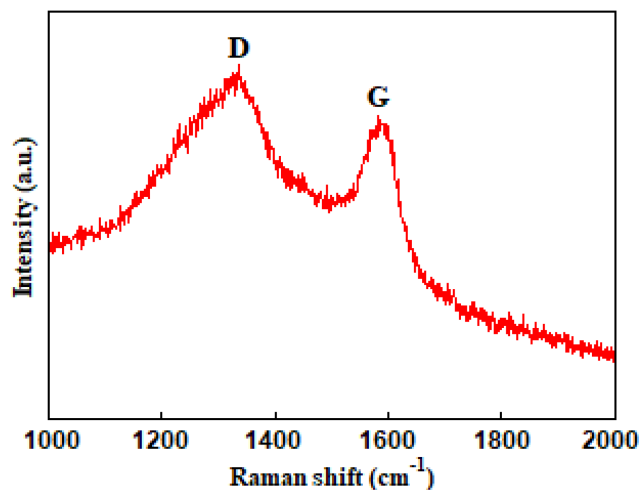


Figure 3. The Raman spectra of AC.

Pores are formed on the surfaces of the carbons as a result of the activating agent evaporating during carbonization, leaving behind the spaces it previously occupied. During the H_3PO_4 impregnation and subsequent heat treatment in an inert environment, the microstructure of the lignocellulosic material is significantly disrupted. This process leads to substantial mass loss due to thermal degradation. As the temperature increases, organic and volatile components are released from the structure. The removal of these components creates voids within the carbon matrix. These voids develop into structural channels—known as pores—resulting in a porous network, as shown in Fig. 4(a). Aydemir *et al.* (2024) and Najmi *et al.* (2020) found similar structures to Fig. 4(b), which depicts the structure of the AC at $\times 200\,000$ magnification.^{35,36}

The proximate analysis of the AC is shown in Table 1. The measurements of moisture content, volatile matter, ash content, and fixed carbon are all part of this investigation. The moisture content of the AC was found to be 4.23%. Low moisture content is advantageous as it enhances the adsorption capacity of the AC by reducing the water content that could occupy adsorption sites. This finding aligns with other studies, which reported moisture content of 3% to 5% for ACs derived from various biomass sources.³⁷ The volatile matter in the AC was 25.63%. A lower volatile matter content indicates a higher degree of carbonization, which improves the adsorption properties of the AC. For comparison, the AC from *Melia azedarach* sawdust had a volatile matter content of approximately 24%,³⁸ whereas rubber wood sawdust-based AC had a volatile matter content of 26%.²⁹ The ash content of the AC was found to be 5.91%. The inorganic residue that remains after carbon is burned is represented by the ash content. Lower ash content is desirable as it

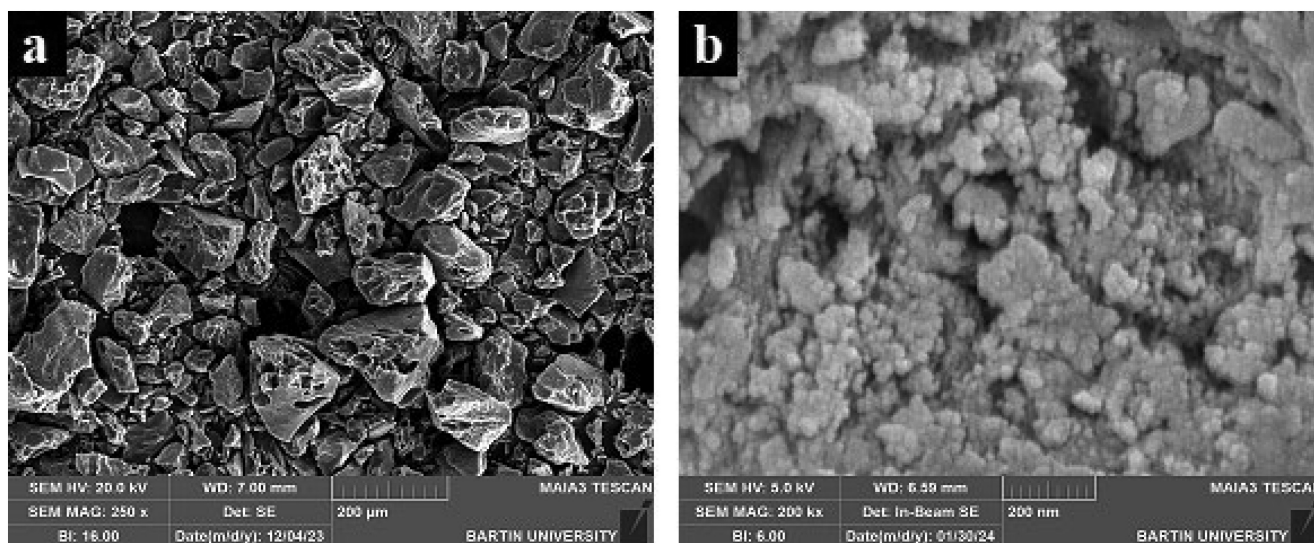


Figure 4. Scanning electron microscopy images of activated carbon: (a) 250 magnification (b) 200 000 magnification.

implies higher purity of the AC. For instance, the AC from oak cups pulp showed an ash content of 5.8%.³⁹ The fixed carbon content of the AC was 64.23%. Fixed carbon is an indicator of the amount of carbon available for adsorption after the removal of volatile matter and ash. Higher fixed carbon content generally correlates with higher adsorption efficiency. Activated carbon produced from *Melia azedarach* sawdust had a fixed carbon content of 62%,³⁸ whereas the AC from rice-husk residue had a fixed carbon content of 65%.⁴⁰ The AC produced from Scots pine wood waste using H_3PO_4 activation demonstrates favorable proximate analysis results. The low moisture and ash contents, combined with high fixed-carbon content, indicate its potential for effective adsorption applications.

The ultimate analysis provided in Table 1 shows the elemental composition of the AC. The carbon content of 65.8% is indicative of the high-quality AC, which is comparable to AC derived from various biomass sources, with carbon content typically between 60% and 70%.⁴¹ High carbon content is essential as it correlates directly with the adsorption capacity of the AC. Activated carbon with higher carbon content typically exhibits greater surface area and porosity, enhancing its ability to adsorb contaminants effectively.⁴⁰ The hydrogen content of 3.0% falls within the range typically observed in high-performing ACs. Adequate hydrogen content contributes to the stability and reactivity of the carbon material. It supports the development of necessary functional groups that can enhance the adsorption of specific pollutants, such as organic compounds. This is supported by findings in other studies where hydrogen contents around 2% to 3% are linked to effective adsorption capabilities.²⁸

The nitrogen content of the AC was 5.6% and other biomass-based ACs found between 1% to 5%.⁴² The oxygen content of 25.6% indicates the presence of oxygen-containing functional groups on the surface of the AC. These groups, which include carboxyl, carbonyl, and hydroxyl groups, improve the carbon surface's hydrophilicity and reactivity. This is essential for the adsorption of polar contaminants such as different types of organic and inorganic pollutants. Activated carbon with significant oxygen content has shown improved adsorption performance for a wide range of contaminants.⁴¹ O content of biomass-derived ACs varied 20%–30%.⁴⁰ The small difference of 1.57% between the fixed carbon content from proximate analysis and the total carbon content from ultimate analysis indicates that a significant portion of the material's carbon remains in the solid phase, with only a minor fraction contributing to volatile emissions. This is particularly relevant for applications such as activated carbon production, where high fixed carbon content is desirable to enhance porosity and surface area. The relatively low volatile matter content suggests that the material has undergone a significant degree of carbonization, making it suitable for adsorption-based applications.

Properties of particleboards

Table 2 presents the physical properties of the particleboards, including thickness swelling (TS) and (WA). The addition of the AC significantly impacted these properties.

The density of particleboard samples ranged from 650 to 685 $kg\cdot m^{-3}$. As only a very small amount of the AC was added relative to the dry-matter weight of the adhesive, no

Table 2. The physical properties of particleboards.

Sample codes	Density (kgm ⁻³)	TS (%) (2h)	TS (%) (24h)	WA (%) (2h)	WA (%) (24h)
Control	685±60 A	32.83±3.45 A	36.84±2.94 A	81.90±5.72 A	92.46±3.22 A
AC-0.5	650±10 A	23.86±1.82 B	27.37±2.45 B	74.25±3.99 B	86.39±3.65 B
AC-1.0	650±40 A	23.04±2.95 C	27.05±3.33 C	72.97±5.58 B	84.76±5.72 B
AC-1.5	670±35 A	21.61±1.28 C	25.85±1.60 C	70.66±6.11 C	83.62±5.33 B

Note: Means in the same column that are followed by the same letters are not significantly different ($P < 0.05$). ± indicates the standard deviation of the measured values.

Abbreviations: TS, thickness swelling and WA, water absorption.

Table 3. The mechanical properties of particleboards.

Sample codes	IB (N·mm ⁻²)	MOR (N·mm ⁻²)	MOE (Nmm ⁻²)
Control	0.42±0.08 A	8.96±1.56 A	1092.06±192.83 A
AC-0.5	0.47±0.05 A	9.31±1.84 A	1266.83±182.95 A
AC-1.0	0.51±0.10 AB	9.45±1.18 A	1460.20±237.44 A
AC-1.5	0.54±0.03 B	11.03±0.7 B	1581.25±150.03 A

Note: Means in the same column that are followed by the same letters are not significantly different ($P < 0.05$). ± indicates the standard deviation of the measured values.

Abbreviations: IB, internal bond strength; MOR, modulus of rupture and MOE, modulus of elasticity.

significant change was observed in the density values of the particleboards. On the other hand, according to the EN 323 (1999) standard, a density fluctuation of up to 10% in particleboards is acceptable. The control sample exhibited the highest TS values of 32.83% after 2 h and 36.84% after 24 h, as well as WA values of 81.90% after 2 h and 89.46% after 24 h. Adding AC significantly reduced these values. The sample with 1.5% AC (AC-1.5) showed the lowest TS values, 21.61% after 2 h and 25.85% after 24 h, and WA values, 70.66% after 2 h and 83.62% after 24 h. High density provides a smoother surface, allowing coatings (such as melamine and laminate) to adhere better. As the density increases, mechanical properties such as modulus of elasticity (MOE) and modulus of rupture (MOR) improve, making the particleboard more durable. However, higher density also has some disadvantages, as it requires more raw materials (wood and resin), increasing production costs. It can also create challenges in transportation, assembly, and processing. In this study, as the amount of added activated carbon was relatively low, the results showed some fluctuations; however, this variation remained within an acceptable range. These results showed that the addition of the AC improved the dimensional stability of particleboards by reducing their swelling and water absorption rates. Similar findings – that incorporating polymer additives could enhance the dimensional stability of cement-bonded particleboards – have been reported in the literature.⁴³ The incorporation of marble dust,⁴⁴ vermiculite,⁴⁵ zeolite,⁴⁶ and calcium carbonate⁴⁷ into wood-based composites boards and panels was found to improve

physical properties such as TS and WA. Conversely, it was demonstrated that adding AC to MDF and particleboard lowered TS and WA values relative to the control group by 2% to 12% and 1% to 13%, respectively.^{5,48,49} The TS and WA values for the particleboards tested in this study tended to reduce with increasing AC content. Exposure to water may lead to degradation and decomposition in wood-based composite materials. However, particleboard might swell and absorb less water, because to ACs porous structure and surface tension.⁵⁰ Porous filler can help lessen the capacity of wood-based boards to absorb water and swell. Fillers with porous structures, like AC, may serve as a barrier to stop water leaking into the wood cells.⁵¹

Table 3 shows the modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB) results for particleboards with and without AC.

The control sample had an IB value of 0.42 N·mm⁻², an MOR of 8.96 N·mm⁻², and an MOE of 1092.06 N·mm⁻². The addition of the AC improved all these properties, with the highest improvements observed in the sample with 1.5% AC (AC-1.5), showing IB, MOR, and MOE values of 0.54 N·mm⁻², 11.03 N·mm⁻², and 1581.25 N·mm⁻², respectively. The observed enhancement may have been influenced by the presence of the AC additive, potentially due to improved interfacial adhesion and filler effects. The IB, MOE, and MOR increased when AC was added during particleboard manufacture, according to the study's findings. Activated carbon contributes to improving the particleboard's mechanical and structural qualities. Perhaps

as a result of its capacity to strengthen particle-resin bonding, the increase in the IB suggests that AC helps to improve internal cohesion inside the board. This may be explained by AC's larger surface area and porosity, which might improve resin penetration and adherence. Consequently, the internal strength of board is strengthened, decreasing the possibility of delamination or failure under pressure. Likewise, the noted increases in MOE and MOR imply that the board's stiffness and flexural strength are improved with the addition of AC. The internal structure may change as a result of the addition of AC, increasing resistance to bending and breaking forces and distributing stress more evenly. These results are consistent with other studies showing that, by strengthening the composite structure, additives like AC can enhance mechanical performance.

When AC is added during the manufacturing of single-layer particleboard, IB, MOE, and MOR values increased. This might be the result of AC's advantageous ability to improve the degree of polycondensation because of its large specific surface area and reactivity. A thickening effect can occur, which typically enhances the strength of the wood-based materials and the morphology of the cured bond lines.⁵²

The chemical and physical interactions between wood particles and AC particles are responsible for the improvement of IB, MOR, and MOE. Activated carbon particles have a large surface area and a large number of functional groups, which allow them to make hydrogen or covalent bonds with the wood particles and the urea-formaldehyde adhesive. The AC particles may also strengthen the interlocking and friction between the wood particles, creating a composite structure that is more compact.^{5,6} Excessive filler content can negatively impact mechanical properties due to agglomeration and matrix discontinuity. However, in this study, the addition of 1.5% activated carbon continued to enhance all mechanical indicators, suggesting that the threshold for excessive filler content was not reached within the tested range.⁵³ In comparison with higher levels (1.0%, 3.0%, and 5.0% w/w), a greater mechanical strength was obtained with lower levels of AC addition (up to 1.5% w/w). The lower AC content, which caused less agglomeration and a more uniform dispersion throughout the composite mixture, explains this circumstance. It was also shown that the mechanical strength of the composite was increased by the addition of the AC to a mixture of several types of polyethylene.⁵⁴

The effect of the addition of AC to the sample particleboards on formaldehyde emissions was evaluated at 0, 6, and 12 months. The findings of the formaldehyde measurement made using the perforator technique are given in Fig. 5.

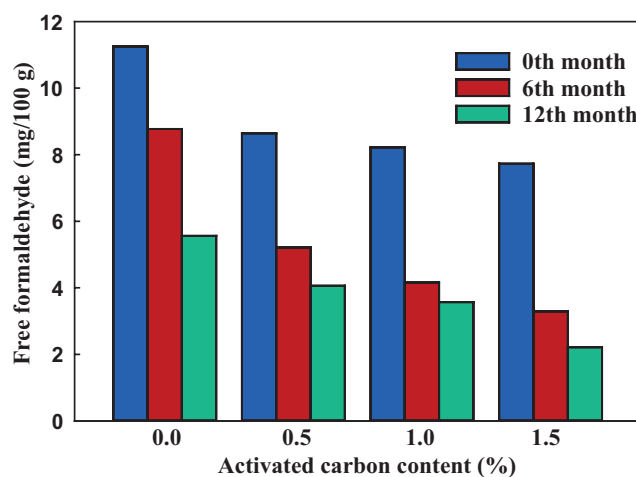


Figure 5. Free formaldehyde emissions from the particleboard samples at 0, 6, and 12 months.

The control sample had the highest formaldehyde emissions, measured at $11.25 \text{ mg} \cdot 100 \text{ g}^{-1}$ initially, reducing to $5.56 \text{ mg} \cdot 100 \text{ g}^{-1}$ after the twelfth month. The addition of AC reduced these emissions significantly. The sample with 1.5% AC (AC-1.5) exhibited the lowest emissions, starting at $7.73 \text{ mg} \cdot 100 \text{ g}^{-1}$ and decreasing to $2.21 \text{ mg} \cdot 100 \text{ g}^{-1}$ after the twelfth month (Fig. 5). The reduced initial formaldehyde emissions in samples with AC added imply that activated carbon contributes to a decrease in the release of free formaldehyde. The large surface area and adsorption capacity of AC may have collected formaldehyde molecules during manufacture, which might explain this. Activated carbon could also have had an impact on resin polymerization, resulting in a more stable network with less diffusion of formaldehyde. These results are consistent with earlier research on the adsorption and chemical interactions between volatile organic molecules and carbon-based materials.^{6,55} The addition of AC not only enhances the mechanical properties and dimensional stability but also significantly reduces the formaldehyde emissions of the particleboards. Activated carbon has a high surface area and a porous structure, and these characteristics are critical for adsorption processes. The BET surface area of the AC can range from 1000 to $1500 \text{ m}^2 \cdot \text{g}^{-1}$, providing ample space for formaldehyde molecules to adhere to the surface.⁵⁶ The microporous and mesoporous structures are particularly effective in capturing small molecules like formaldehyde.⁵⁷ The surface chemistry of the AC plays a significant role in formaldehyde adsorption. Functional groups such as hydroxyl, carbonyl, and carboxyl groups on the surface of the AC can interact with formaldehyde molecules through hydrogen bonding and other intermolecular forces.⁵⁸ In comparison with the control group, the particleboards

produced exhibited a 24% reduction in formaldehyde emissions after the sixth month.²⁴ The addition of the AC to particleboards significantly improves their physical and mechanical properties while effectively reducing formaldehyde emissions. These enhancements make the AC a valuable additive for producing high-performance, environmentally friendly materials.

Conclusion

The comprehensive evaluation of the particleboards produced in this study demonstrates the significant potential of incorporating AC into UF resin as a sustainable and effective approach for reducing formaldehyde emissions and improving the properties of particleboards in the wood-based composite industry. The incorporation of AC at different levels (ranging from 0.5% to 1.5% based on the dry weight of the adhesive) results in a substantial reduction in formaldehyde emissions. When AC was added, formaldehyde emissions were significantly reduced – by as much as 50% – in comparison with particleboards without AC. Nevertheless, formaldehyde emissions also displayed a minor increasing trend as the AC level rose, indicating that the adsorption capability of AC may become saturated or that its presence may impede resin curing beyond a certain threshold. This reduction aligns with environmental and health safety standards, mitigating the potential health risks associated with formaldehyde exposure.

The integration of AC into UF resin also leads to notable improvements in the physical and mechanical properties of the particleboards. The production of AC from Scots pine wood residues using H₃PO₄ activation was shown to be a suitable method for obtaining high-quality AC. The AC exhibited advantageous structural characteristics, including a high BET surface area and micropore volume. These properties contribute to its exceptional adsorption capabilities, allowing for effective reduction of formaldehyde emissions in the particleboards.

Importantly, this study highlighted the environmental and economic benefits of utilizing biomass waste, such as Scots pine wood residues, as a raw material for AC production. By transforming waste materials into valuable resources, this approach not only addresses waste management challenges but also contributes to the development of a circular economy. The incorporation of AC into UF resin not only meets environmental and health safety standards but also offers a pathway towards a more environmentally friendly and resource-efficient wood-based composite industry. By enhancing the performance of particleboards and reducing their environmental impact, the integration of AC provides

a promising avenue to achieve sustainable and high-quality composite materials in various industrial applications.

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Author contributions

Mehmet Emin Ergün and Filiz Koyuncu: conceptualization, methodology, formal and statistical analysis, and original draft. İsmail Özlüsoylu: material preparation and testing, writing and editing of original draft. Abdullah İstek: data curation, writing and editing of original draft.

Conflict of interest

The authors declare no conflict of interest.

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