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THE IMPACT OF ACTIVATED CARBON FROM BLACK PINE (*PINUS NIGRA*) WOOD WASTE ON PARTICLEBOARD PERFORMANCE AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

This study investigates the use of activated carbon derived from black pine (*Pinus nigra*) wood waste in the production of particleboards. The activated carbon was synthesized through chemical activation with zinc chloride ($ZnCl_2$) to increase its surface area and pore structure. It achieved a high BET surface area of 1003 m^2/g, indicating strong potential for applications requiring substantial adsorption capacity. Activated carbon was incorporated into the particleboard at concentrations of 2%, 5%, and 8%. Its addition resulted in a 48% reduction in formaldehyde emissions compared with the control group, demonstrating significant potential for improving indoor air quality. The mechanical properties of the particleboards were also enhanced, with the modulus of rupture (MOR) increasing by approximately 20%. These findings show that incorporating activated carbon not only reduces environmental impact but also improves the functional performance of particleboards. The production process emphasizes sustainability by utilizing waste materials, thereby reducing environmental degradation and promoting eco-friendly practices within the wood panel industry. This approach supports the development of high-performance, sustainable building materials, aligned with contemporary environmental and social responsibility objectives.

Keywords: black pine, formaldehyde emissions, activated carbon, particleboard

INTRODUCTION

Growing concerns about environmental sustainability, indoor air quality, and human health have intensified the demand for innovative, eco-conscious materials in the wood-based composite industry. Particleboards, widely used in construction and furniture manufacturing, are traditionally bonded with urea-formaldehyde (UF) adhesives (Kurt, 2022), which are a major source of formaldehyde emissions – a volatile organic compound (VOC) linked to respiratory problems and classified as a human carcinogen by the International Agency for Research on Cancer (IARC) (Yu and Crump, 1999). As a result, considerable research has focused on modifying particleboard compositions to lower these emissions while maintaining mechanical and physical performance (İstek et al., 2018; Özlüsoylu and İstek, 2018).

Activated carbon (AC), owing to its high specific surface area and well-developed porosity, has demonstrated considerable potential as a formaldehyde scavenger in composite panels (Zamani et al., 2022). Although traditionally produced from precursors such as coconut shells or coal, generating AC from renewable biomass waste offers a more sustainable and circular alternative. Several studies have demonstrated

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the feasibility of using agricultural and lignocellulosic residues for AC production (Koyuncu et al., 2022; Teymur et al., 2025). For example, AC derived from orange peel waste has been shown to reduce formaldehyde emissions by up to 45.25% after three months while simultaneously enhancing mechanical properties (Ergun et al., 2025). Likewise, incorporating small amounts (0.75–1.5%) of coconut shell-based AC into UF adhesives has improved bending strength, increased water resistance, and lowered free formaldehyde levels, attributed to the strong adsorption capability of AC (Kawalerczyk et al., 2024).

Black pine (*Pinus nigra*) wood waste – widely available as a byproduct of forestry and sawmilling operations – represents an underutilized but promising feedstock for AC production. Through chemical activation processes such as $ZnCl_2$ treatment, this biomass can be converted into highly porous activated carbon with a large surface, thereby enhancing its capacity to adsorb hazardous gases and VOCs (Ergun et al., 2025). Previous studies have reported that increased AC content progressively decreases formaldehyde emissions in particleboards, accompanied by improvements in density, strength, and termite resistance (Indrayani et al., 2022).

This study evaluates the incorporation of activated carbon derived from black pine wood waste into particleboards at concentrations of 2%, 5%, and 8% (based on dry adhesive weight). The activated carbon, produced via $ZnCl_2$ chemical activation, exhibited a high BET surface area (1003 m^2/g), indicating substantial adsorption capacity. The aim is to determine its effectiveness in reducing formaldehyde emissions, improving mechanical performance (e.g., modulus of rupture), and enhancing environmental sustainability through the valorization of industrial biomass waste.

MATERIALS AND METHODS

Materials

Black pine (*Pinus nigra*) wood waste was obtained from local sawmill residues, including sawdust, shavings, and trimmings. The material was air-dried to reduce moisture content below 10%, then milled and sieved to achieve a uniform particle size suitable for carbonization (approximately 0.5–1 mm). Deciduous (*Fagus orientalis*, *Carpinus betulus*, and *Populus nigra*) and coniferous (*Pinus nigra*) species supplied the wood chips used for particleboard production. Urea-formaldehyde (UF) resin served as the primary adhesive and met commercial standards for wood-based composites. At 22°C, the urea-formaldehyde (UF) adhesive exhibited a density of 1265–1285 kg/m^3, a viscosity of 270–310 mPa·s, and a solid content of 65% ±1. A 20% ammonium chloride (NH_4Cl) solution was used as a curing agent at 1.5% of the adhesive weight. Formaldehyde content was determined using a Spectroquant test kit. All chemicals, supplied by Merck (Darmstadt, Germany) and Fluka (Buchs, Switzerland), were of analytical-grade purity.

Methods

Production of activated carbon

AC was produced by mixing 100 g of $ZnCl_2$ with 250 mL of distilled water and 200 g of black pine wood waste. The mixture was stirred thoroughly and allowed to stand at room temperature for one day to ensure sufficient interaction between the activator and the biomass. Zinc chloride ($ZnCl_2$) was selected due to its well-established efficiency in producing high surface area, microporous activated carbon. As a dehydrating agent, $ZnCl_2$ promotes the decomposition of organic matter while suppressing tar formation during carbonization, resulting in higher yield and enhanced porosity (Yorgun et al., 2009). Compared with other chemical activators such as KOH or H_3PO_4, $ZnCl_2$ operates effectively at moderate temperatures and produces activated carbon with a favorable balance of surface area, pore volume, and structural stability – attributes critical for adsorption-based applications, including formaldehyde removal (Li et al., 2023).

After impregnation, the mixture was dried at 80°C for one day and then carbonized for 90 min at 600°C under an argon flow of 50 mL/min. Following activation, the material was cooled to room temperature and rinsed repeatedly with distilled water until a neutral pH was achieved. The resulting AC was dried at 100°C for 6 h and ground to the required particle size for subsequent use.

Production of particleboards

Three-layer particleboards were manufactured using separate surface and core wood chips. The distribution of chips was 20% for the top layer, 20% for the bottom layer, and 60% for the core. Chips were dried to

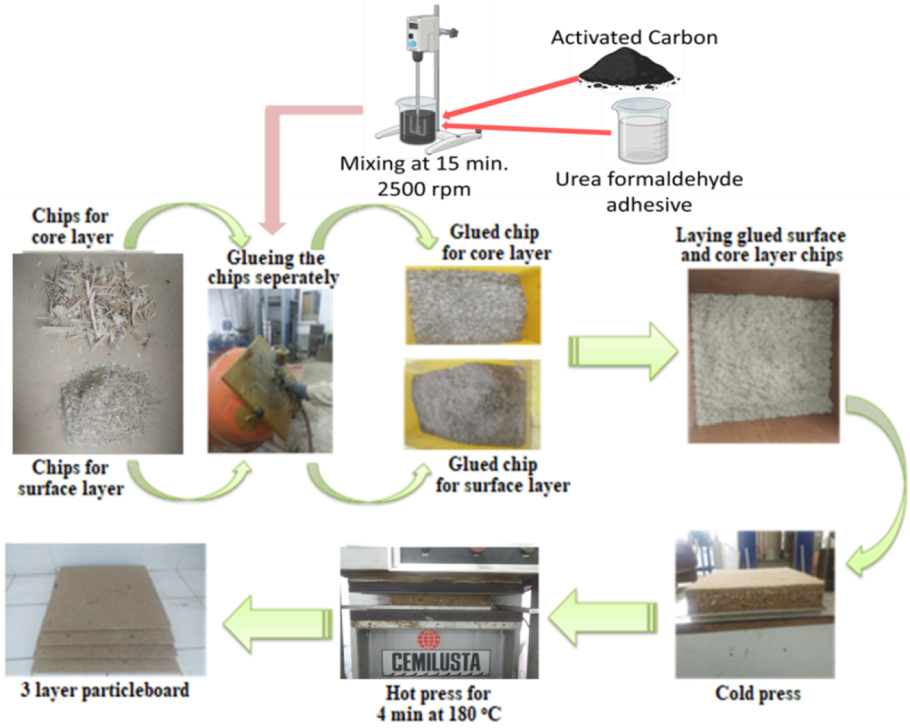

Fig. 1. The production process of the particleboard
Ryc. 1. Proces produkcji płyty wiórowej

a moisture content of 1–3%. UF adhesive containing various AC concentrations (0%, 2%, 5%, and 8% by weight of the dry adhesive) was applied, with surface chips receiving 10% adhesive and core chips 8%. The glued chips were arranged in a 400 × 400 × 300 mm mold and cold pressed to pre-form the mat. Hot-pressing was performed at 180°C under a specific pressure of 2–4 N/mm^2 for 4 min, yielding boards with a target density of 650 kg/m^3 and a thickness of 16 mm. After pressing, the boards were conditioned at 20°C ±2°C and 65% ±5% relative humidity to stabilize their physical properties. The particleboard production process is shown in Fig. 1.

Characterization

The structural properties of the AC, including BET surface area and pore volume, were measured using nitrogen adsorption/desorption isotherms on a Quantachrome Autosorb IQ BET analyzer. Samples were degassed at 120°C for 3 h before analysis. X-ray diffraction (XRD) patterns (10–70°) were recorded using a Rigaku SmartLab device. Microstructural observations were conducted with a Tescan Maia3 Xmu scanning electron microscope (SEM) operated at 20.0 kV, with gold coating applied to enhance conductivity. The physical, mechanical, and environmental properties of the particleboards were evaluated according to relevant standards. Mechanical properties, including bending strength and modulus of elasticity, were assessed following EN 310 (1999). Sampling, cutting, and inspections were performed according to EN 326-1 (1999). Formaldehyde emissions were determined using the perforator method specified in ISO 12460-2:2024, ensuring compliance with safety and health standards. Additional performance evaluations were conducted in accordance with ASTM D1037 (2006) to verify compliance with international standards.

RESULTS AND DISCUSSION

The BET analysis of activated carbon (AC) derived from black pine wood waste via $ZnCl_2$ activation is summarized in Table 1.

Table 1. BET results of activated carbon
Tabela 1. Wyniki analizy BET węgla aktywnego

	Surface area m^2/g	V_{micro} cm^3/g	V_{mezo} cm^3/g	V_{total} cm^3/g	D_p nm	% yield
Activated carbon	1003	0.412	0.083	0.495	1.26	30.86

The activated carbon (AC) exhibited a high specific surface area of 1003 m^2/g and a total pore volume of 0.495 cm^3/g. Micropores dominated the pore structure (Vmicro = 0.412 cm^3/g; Vmezo = 0.083 cm^3/g), with an average pore diameter of 1.26 nm. The activation yield was 30.86%, indicating efficient carbonization and pore development. This high surface area and micropore-dominant structure are particularly effective for formaldehyde adsorption, as micropores (<2 nm) provide strong adsorption potentials at low relative pressures (Fomkin, 2005).

These porosity characteristics confirm the material's suitability for capturing small gaseous molecules such as formaldehyde. Similar results were reported by Yang and Cannon (2022), who produced AC from pine sawdust using steam bursting, achieving a surface area of 962 m^2/g and pore volume of 0.526 cm^3/g. Singh et al. (2019) produced phenolic-based AC spheres with BET surface areas ranging from 836 to 3694 m^2/g, though these values were strongly influenced by burn-off rate and starting F/P ratios. Ma et al. (2020) achieved ultra-high surface areas (up to 3839 m^2/g) using optimized biomass activation for acetone and CO_2 adsorption applications; however, such high values often come at the cost of structural fragility or high activation losses. In comparison, the black pine-based AC used in this study offers a balanced and sustainable profile – high surface area, dominant microporosity, and moderate yield – without the need for extreme activation temperatures or complex precursors. This supports its effectiveness in adsorption-driven applications (e.g., formaldehyde capture) and as a functional additive in composite materials such as particleboards.

SEM images and the XRD pattern of the AC are shown in Fig. 2.

The SEM image (Fig. 2) shows a highly porous, irregular surface with evident cavities and channels. This morphology is characteristic of $ZnCl_2$ activation, which promotes the removal of volatiles and the

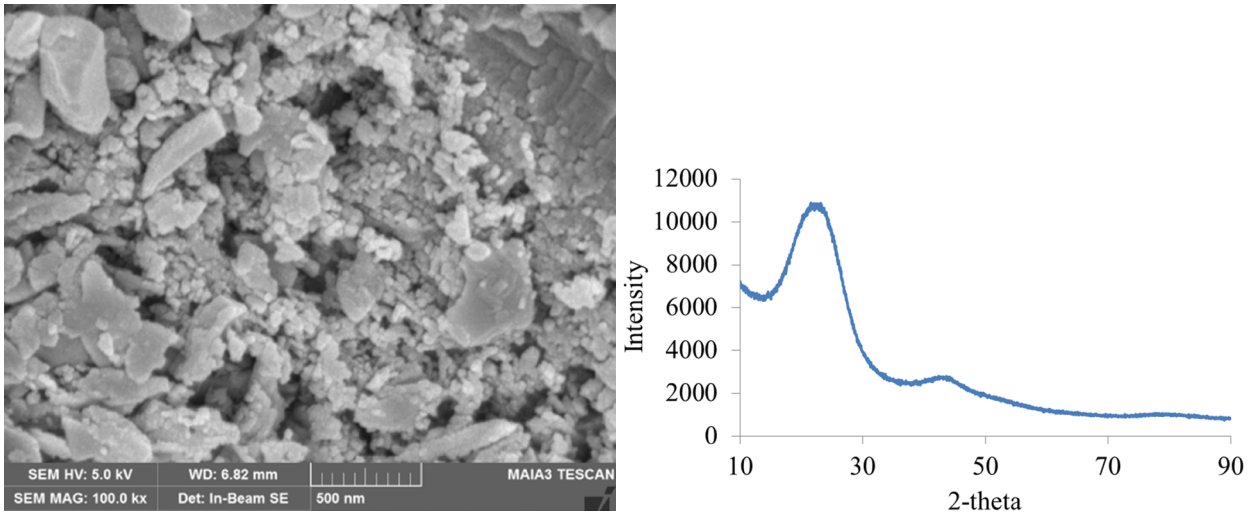

Fig. 2. SEM image (left) and XRD pattern of activated carbon (right)
Ryc. 2. Obraz SEM (po lewej) oraz dyfraktogram rentgenowski XRD węgla aktywnego (po prawej)

formation of a well-developed pore structure. These features enhance surface accessibility and adsorption capacity, crucial for VOC capture. Comparable morphologies were observed by Indrayani et al. (2022) in bagasse-based activated charcoal and by Ergun et al. (2025) in AC produced from orange peel waste, with both studies indicating that such structures contribute to improved adsorption performance, including formaldehyde capture in particleboards.

The XRD pattern (Fig. 2) displays broad peaks at approximately 2θ ≈ 22° and 43°, indicating an amorphous carbon structure with limited graphitic domains. This partially ordered structure is typical of biomass-derived activated carbons, where incomplete carbonization leads to turbostratic carbon stacking rather than crystalline graphite. Similar amorphous patterns were reported by Kawalerczyk et al. (2024) in coconut shell-derived activated carbon, and such structural disorder is associated with an abundance of adsorption sites. These structural characteristics further support the suitability of black pine-derived AC for adsorption-dominant applications, including formaldehyde reduction.

Mechanical properties of particleboards

The modulus of rupture (MOR) and modulus of elasticity (MOE) values for particleboards with varying levels of AC are presented in Table 2.

Table 2. Mechanical properties of particleboards, N/mm²
Tabela 2. Właściwości mechaniczne płyt wiórowych, N/mm²

Codes	AC-0	AC-2	AC-5	AC-8
MOR	13.36	14.83	15.55	13.49
MOE	2064	2106	2230	2016

Compared to the control group (0% AC, MOR: 13.36 N/mm², MOE: 2064 N/mm²), the addition of AC initially improved mechanical properties. At 2% AC, MOR and MOE increased to 14.83 N/mm² and 2106 N/mm². The optimal performance was achieved at 5% AC, where MOR and MOE reached at 15.55 N/mm² (16.4% increase) and 2230 N/mm² (8% improvement), respectively. These enhancements are attributed to the high surface area and porosity of AC, which improve adhesive bonding and stress distribution. However, at 8% AC, both MOR (13.49 N/mm²) and MOE (2016 N/mm²) declined; due to excessive AC content disrupts matrix homogeneity or impedes adhesive curing. These trends are consistent with earlier research. Kawalerczyk et al. (2024) found that adding 0.75–1.5% coconut shell-based AC improved bending strength and elasticity, which they attributed to enhanced interactions with the urea-formaldehyde matrix. Similarly, Indrayani et al. (2022) reported that bagasse-derived AC improved mechanical strength up to approximately 6% loading, beyond which the properties plateaued or declined.

Free formaldehyde content of particleboards

The effects of AC incorporation on formaldehyde emissions were evaluated at 0 months using the perforator method, and the results are presented in Fig. 3.

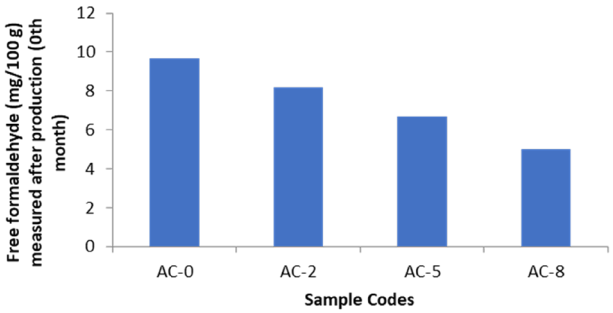

Fig. 3. Free formaldehyde content of particleboards
Ryc. 3. Zawartość wolnego formaldehydu w płytach wiórowych

Free formaldehyde emissions decreased significantly with increasing AC content. At 8% AC, emissions were reduced by 48% compared to the control. This reduction is attributed to the high BET surface area of the AC (1003 m²/g), which enables effective adsorption of formaldehyde molecules. These results are consistent with previous research: activated carbon derived from orange peel waste reduced formaldehyde emissions by 45.25% after three months (Ergun et al., 2025), while up to 80% reduction was reported when 50% charcoal was incorporated into the core layer of particleboards (Kowaluk et al., 2016). Together, these comparisons reinforce the present study's conclusion

that activated carbon is highly effective in mitigating formaldehyde emissions and, when optimally dosed, can also enhance mechanical performance.

Despite these promising results, practical considerations must be addressed when assessing the industrial feasibility of incorporating AC into particleboard production. Chemical activation – particularly when using $ZnCl_2$ – may increase production expenses relative to conventional manufacturing methods. Additional requirements, such as precise temperature control, inert gas environments (argon), and post-processing steps including washing and drying, further add to the complexity and energy demand of the process. Scalability presents another challenge: while laboratory-scale production ensures consistency, large-scale manufacturing may introduce variability in AC quality that could influence performance. Environmental concerns related to $ZnCl_2$ disposal also require careful management to prevent secondary pollution. These factors highlight the need for cost-benefit evaluation and further investigation into greener or more economical activation methods for large-scale application.

CONCLUSION

This study demonstrated that activated carbon (AC) derived from black pine (*Pinus nigra*) wood waste can simultaneously enhance the environmental and mechanical performance of particleboards. The AC, produced through $ZnCl_2$ chemical activation, achieved a high BET surface area (1003 m^2/g), enabling efficient formaldehyde adsorption and resulting in a 48% reduction in emissions at 8% AC content. Mechanical properties were also improved, with the greatest increases in the modulus of rupture and modulus of elasticity occurring at 5% AC, likely due to enhanced interfacial bonding and stress distribution. At 8% AC, however, these improvements diminished slightly, indicating the presence of an optimal AC loading level. Beyond technical performance, the use of forestry residues as a precursor for AC contributes to sustainable materials development by transforming waste into a high-value additive. Overall, these findings demonstrate that black pine-based activated carbon is a promising, eco-efficient solution for developing low-emission, high-strength particleboards that align with contemporary sustainability goals. Future research could investigate the long-term durability of AC-enhanced particleboards under variable environmental conditions and include life cycle assessments to fully quantify environmental impacts and benefits across the material's lifespan.

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WPŁYW WĘGLA AKTYWNEGO Z ODPADÓW DREWNA SOSNY CZARNEJ (*PINUS NIGRA*) NA WŁAŚCIWOŚCI PŁYT WIÓROWYCH I ZRÓWNOWAŻONY ROZWÓJ ŚRODOWISKOWY

ABSTRAKT

W artykule przeanalizowano możliwości wykorzystania węgla aktywnego otrzymywanego z odpadów drewna sosny czarnej (*Pinus nigra*) do produkcji płyt wiórowych. Węgiel aktywny został wytworzony metodą aktywacji chemicznej z użyciem chlorku cynku ($ZnCl_2$), co pozwoliło zwiększyć jego powierzchnię właściwą i rozwój struktury porów. Uzyskany materiał charakteryzował się wysoką powierzchnią BET na poziomie 1003 m^2/g, co potwierdza jego przydatność w zastosowaniach wymagających dużej zdolności adsorpcyjnej. Węgiel aktywny wprowadzono do płyt wiórowych w stężeniach 2%, 5% i 8%. Dodatek ten spowodował redukcję emisji formaldehydu o 48% w porównaniu z grupą kontrolną, co wskazuje na potencjał do znaczącej

poprawy jakości powietrza wewnętrznego. Właściwości mechaniczne płyt również się poprawiły – moduł wytrzymałości na zginanie (MOR) wzrósł około 20%. Wyniki te dowodzą, że włączenie węgla aktywnego nie tylko ogranicza wpływ środowiskowy, lecz także zwiększa funkcjonalne właściwości płyt wiórowych. W procesie produkcji uwzględniono aspekt zrównoważonego rozwoju przez wykorzystanie materiałów odpadowych, co przyczynia się do ograniczenia degradacji środowiska i promuje praktyki przyjazne naturze w przemyśle płyt drewnopochodnych. To innowacyjne podejście wspiera rozwój wysokowydajnych, zrównoważonych materiałów budowlanych, wpisując się w cele współczesnej odpowiedzialności środowiskowej i społecznej.

Słowa kluczowe: sosna czarna, emisja formaldehydu, węgiel aktywny, płyta wiórowa