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TEXTURAL PROPERTIES OF BENTONITE–SAWDUST CARBON COMPOSITES AFTER METAL-CHLORIDE-ASSISTED CARBONIZATION

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Abstract. The aim of this study was to evaluate the textural changes produced by metal-chloride-assisted carbonization of wood sawdust in a bentonite matrix and to compare FeCl₃-, NiCl₂-, and CoCl₂-containing formulations under the same thermal regime. Composites were prepared from 2 g of bentonite and 1 g of sawdust with the corresponding metal chloride, dried at 80 °C for 24 h, and carbonized at 550 °C for 1 h under argon. Nitrogen physisorption at 77.35 K was used to determine BET specific surface area and BJH pore parameters for raw bentonite and three carbonized composites: B-Co (0.75 g CoCl₂), B-Fe (0.50 g FeCl₃), and B-Ni (0.50 g NiCl₂). The BET surface area increased from 45.836 m² g⁻¹ for raw bentonite to 223.915, 248.350, and 233.406 m² g⁻¹ for B-Co, B-Fe, and B-Ni, respectively, corresponding to 4.89-, 5.42-, and 5.09-fold increases. At the same time, BJH adsorption pore volume

decreased from $0.012 \text{ cm}^3 \text{ g}^{-1}$ to $0.007\text{--}0.008 \text{ cm}^3 \text{ g}^{-1}$, and the characteristic BJH pore radius decreased from 2.152 nm to 1.626–1.955 nm. These results indicate that the additional nitrogen-accessible surface is not explained by an increase in BJH mesopore volume and is consistent with the development of finer porosity and carbon–clay interfacial surface. Among the tested formulations, B-Fe exhibited the highest BET area. Thus, FeCl_3 -assisted carbonization provides the strongest basis for subsequent structural characterization and adsorption testing, although graphitic ordering and sorption capacity require independent verification.

Keywords: bentonite, sawdust, catalytic carbonization, metal chlorides, BET surface area, BJH porosity, carbon composite

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МЕТАЛЛ ХЛОРИДТЕРІ ҚАТЫСЫНДА КАРБОНИЗАЦИЯЛАНҒАН БЕНТОНИТ–ҮГІНДІ КӨМІРТЕК КОМПОЗИТТЕРІНІҢ ТЕКСТУРАЛЫҚ ҚАСИЕТТЕРІ

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Аннотация. Зерттеудің мақсаты — металл хлоридтері қатысында бентонит матрицасындағы ағаш үгіндісін карбонизациялау нәтижесінде болатын текстуралық өзгерістерді бағалау және бірдей термиялық режимде FeCl_3 -

, NiCl_2 - және CoCl_2 -құрамды композицияларды салыстыру. Композиттер 2 г бентониттен, 1 г ағаш үгіндісінен және тиісті металл хлоридінен дайындалып, 80 °C температурада 24 сағат кептірілді және аргон атмосферасында 550 °C-та 1 сағат карбонизацияланды. Бастапқы бентонит пен үш карбонизацияланған композиттің - В-Со (0,75 г CoCl_2), В-Fe (0,50 г FeCl_3) және В-Ni (0,50 г NiCl_2) - БЭТ бойынша меншікті бет ауданы мен ВJH кеуектілік параметрлері 77,35 К температурада азоттың физикалық адсорбциясы әдісімен анықталды. БЭТ меншікті бет ауданы бастапқы бентонит үшін 45,836 м²/г-нан В-Со, В-Fe және В-Ni үлгілері үшін тиісінше 223,915; 248,350 және 233,406 м²/г-ға дейін артты, бұл 4,89; 5,42 және 5,09 есе өсімге сәйкес келеді. Сонымен қатар ВJH бойынша адсорбциялық кеуек көлемі 0,012 см³/г-нан 0,007–0,008 см³/г-ға дейін, ал сипаттамалық кеуек радиусы 2,152 нм-ден 1,626–1,955 нм-ге дейін төмендеді. Бұл нәтижелер азот молекулаларына қолжетімді қосымша беттің артуы ВJH бойынша мезокеуек көлемінің ұлғаюымен түсіндірілмейтінін және оның ұсақ кеуектіліктің дамуы мен көміртек–саз фазалары арасындағы интерфейстік беттің қалыптасуына сәйкес келетінін көрсетеді. Зерттелген құрамдардың ішінде В-Fe үлгісі ең жоғары БЭТ меншікті бет ауданымен сипатталды. Осылайша, FeCl_3 қатысындағы карбонизация кейінгі құрылымдық зерттеулер мен адсорбциялық сынақтар үшін ең перспективалы нұсқа болып табылады. Алайда графиттік реттелу дәрежесі мен сорбциялық сыйымдылық жеке эксперименттік әдістермен расталуы тиіс.

Түйін сөздер: бентонит, ағаш үгіндісі, каталитикалық карбонизация, металл хлоридтері, БЭТ меншікті беті, ВJH кеуектілігі, көміртеккі композит

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ТЕКСТУРНЫЕ СВОЙСТВА БЕНТОНИТ–УГЛЕРОДНЫХ КОМПОЗИТОВ ПОСЛЕ КАРБОНИЗАЦИИ В ПРИСУТСТВИИ ХЛОРИДОВ МЕТАЛЛОВ

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Аннотация. Цель исследования заключалась в оценке текстурных изменений, возникающих при карбонизации древесных опилок в бентонитовой матрице в присутствии хлоридов металлов, и сравнении композиций, содержащих FeCl_3 , NiCl_2 и CoCl_2 , при одинаковом температурном режиме. Композиты готовили из 2 г бентонита, 1 г древесных опилок и соответствующего хлорида металла, сушили при 80 °С в течение 24 ч и карбонизировали при 550 °С в течение 1 ч в атмосфере аргона. Удельную поверхность по БЭТ и параметры пористой структуры по ВЖН определяли методом физической адсорбции азота при 77,35 К для исходного бентонита и трёх карбонизированных композитов: В-Со (0,75 г CoCl_2), В-Fe (0,50 г FeCl_3) и В-Ni (0,50 г NiCl_2). Удельная поверхность по БЭТ увеличилась с 45,836 м²/г для исходного бентонита до 223,915; 248,350 и 233,406 м²/г для В-Со, В-Fe и В-Ni соответственно, то есть в 4,89; 5,42 и 5,09 раза. Одновременно объём пор по адсорбционной ветви ВЖН уменьшился с 0,012 до 0,007–0,008 см³/г, а характерный радиус пор — с 2,152 до 1,626–1,955 нм. Полученные данные показывают, что увеличение доступной для азота поверхности не обусловлено ростом объёма мезопор по ВЖН и согласуется с развитием более тонкой пористости и межфазной поверхности углерод–глина. Среди исследованных составов образец В-Fe характеризовался максимальной удельной поверхностью по БЭТ. Следовательно, карбонизация в присутствии FeCl_3 представляет наиболее перспективный вариант для дальнейшей структурной характеристики и адсорбционных испытаний. Вместе с тем степень графитного упорядочения и сорбционная ёмкость должны быть подтверждены независимыми экспериментальными методами.

Ключевые слова: бентонит, древесные опилки, каталитическая карбонизация, хлориды металлов, удельная поверхность БЭТ, пористость ВЖН, углеродный композит

Introduction. Bentonite is a layered aluminosilicate whose sorption behavior is governed by the accessible external surface, interlayer charge, exchangeable cations, and the distribution of pores between mineral particles. Its availability and chemical stability make it a practical mineral matrix for sorbent preparation, but raw bentonite does not automatically provide the surface area required for every separation problem. Acid activation, thermal treatment, incorporation of carbon, and formation of mineral–biochar composites are therefore used to modify its surface and pore architecture. Studies published in the same journal have demonstrated the relevance of bentonite and other modified carbonaceous sorbents to water treatment, while recent work on bentonite–biochar systems shows that combining a clay phase with biomass-derived carbon can substantially alter accessible porosity (Ilyasova et al., 2022; Murzakassymova et al., 2022; Egbedina et al., 2023).

Co-pyrolysis is attractive because the mineral and carbon phases are generated or

reorganized in the same thermal step. Wood-derived biomass supplies a lignocellulosic carbon precursor, whereas bentonite provides an inorganic framework that can restrict shrinkage, create interfaces, and influence heat and mass transfer during devolatilization. Co-pyrolysis of wood chips with bentonite at 550 °C has been shown to modify the microstructure and stability of the resulting char, confirming that clay minerals participate in the evolution of the solid rather than acting only as an inert diluent (Wang et al., 2022). Related bentonite–biochar composites produced from plant residues also display surface areas in the hundreds of square metres per gram when carbonization and activation are appropriately controlled (Egbedina et al., 2023; Yang et al., 2023).

Transition-metal salts provide an additional means of steering the thermal conversion of biomass. Iron, nickel, and cobalt compounds can catalyze bond cleavage, dehydration, deoxygenation, aromatization, and rearrangement of the carbonaceous residue. The effect is sensitive to both the metal and its counter-ion. For example, FeCl₃-assisted pyrolysis has produced micropore-rich carbon with a high surface area, while nickel salts have been reported to change biochar yield, aromaticity, morphology, and specific surface area (Lugovoy et al., 2019; Xia et al., 2023; Hu et al., 2023). At higher temperatures, Fe, Co, and Ni can also catalyze graphitic ordering, but the term graphitization requires direct structural evidence such as Raman spectroscopy and X-ray diffraction rather than nitrogen sorption alone (Hunter et al., 2022; Farid et al., 2023).

The aim of this study was to obtain porous carbon–mineral composites by carbonizing bentonite–sawdust mixtures in the presence of FeCl₃, NiCl₂, or CoCl₂ and to determine how the tested formulations affect nitrogen-physisorption textural parameters under an identical thermal regime. The specific objectives were to: (1) prepare the three metal-chloride-containing composites using the same bentonite/sawdust ratio and carbonization conditions; (2) determine BET specific surface area and BJH pore parameters; (3) compare the textural response of the Fe-, Ni-, and Co-containing formulations; (4) interpret the relationship between the BET-area increase and the BJH mesopore contribution without assigning unmeasured structural properties; and (5) identify the formulation that provides the strongest basis for subsequent structural and adsorption studies. Because all composites were carbonized at a single temperature of 550 °C, the study does not claim a comparative temperature effect.

Scientific novelty. The novelty of the work lies in the comparative textural assessment of bentonite–sawdust composites produced by one-step carbonization at 550 °C with FeCl₃, NiCl₂, and CoCl₂ under a common preparation scheme. The study demonstrates an approximately fivefold increase in BET surface area while the BJH mesopore volume decreases, and it identifies the FeCl₃-containing formulation as the material with the highest measured BET area among the tested samples.

Practical significance. The results provide a screening basis for selecting carbon–clay formulations for subsequent development as adsorbent materials or catalyst supports. In the present data set, B-Fe is the priority formulation for further XRD/Raman characterization and equilibrium sorption experiments; however, the current textural data alone do not establish adsorption capacity or mechanical performance.

Literature review. Nitrogen physisorption remains the standard experimental basis for comparing the accessible surface and mesopore structure of porous solids. The Brunauer–Emmett–Teller (BET) treatment relates multilayer adsorption to a monolayer-equivalent capacity and is widely used to report specific surface area (Brunauer et al., 1938). Pore-size distributions in the mesopore range are often evaluated by the Barrett–Joyner–Halenda (BJH) method, which interprets capillary condensation through a Kelvin-type relationship (Barrett et al., 1951). The IUPAC technical report emphasizes that BET area and pore-size analysis are model-dependent quantities; interpretation should therefore distinguish total apparent surface from the portion of pore space represented by a particular pore-size model (Thommes et al., 2015). This distinction is particularly important for heterogeneous mineral–carbon composites, in which micropores, mesopores, particle contacts, and phase interfaces can coexist.

Published work on biomass-derived carbons demonstrates that metal salts can change both carbon yield and pore development. Lugovoy et al. (2019) compared several metal chlorides during wheat-straw pyrolysis and found that transition-metal chlorides alter thermal decomposition and the properties of the solid residue. Zhang et al. (2021) used FeCl_3 to regulate the hierarchical pore structure of bamboo-derived carbon and linked iron-assisted treatment with a large increase in accessible surface. Xia et al. (2023) directly compared iron salts and reported that FeCl_2 and FeCl_3 favored micropore-dominated chars with a BET surface area of about $505 \text{ m}^2 \text{ g}^{-1}$ under their conditions. The numerical value is not transferable to the present system because feedstock, salt loading, reactor design, washing, and thermal history differ, but the study establishes that chloride-containing iron precursors can promote fine pore formation.

Nickel salts show a similarly strong dependence on counter-ion and thermal conditions. Hu et al. (2023) found that nickel salts affected volatile release, char yield, specific surface area, and the aromatic structure of reed-derived biochar; NiCl_2 was particularly effective at changing product distribution, while NiSO_4 gave the largest surface area in that specific system. Comparisons among catalysts therefore cannot be reduced to a universal $\text{Fe} > \text{Ni} > \text{Co}$ sequence. Catalyst loading, hydration state, feed composition, heating profile, mineral matter, and any post-carbonization washing determine the phases present during and after pyrolysis.

Graphitic ordering is a related but separate property. Iron-catalyzed graphitization has been studied extensively because dissolved or transient metal–carbon phases can facilitate carbon reorganization (Hunter et al., 2022). Biomass-derived graphitic carbons have also been produced with Fe, Co, and Ni catalysts, generally at temperatures well above those used here, with the degree of ordering established by Raman, XRD, electron microscopy, or complementary methods (Gai et al., 2021; Farid et al., 2023). In a study limited to BET/BJH data at 550°C , it is therefore more defensible to use the term metal-chloride-assisted carbonization and to discuss pore development rather than to claim catalytic graphitization.

Bentonite–biochar research provides a direct materials context. Egbedina et al. (2023) obtained porous bentonite–coconut husk materials with BET areas of 284 – 456

$\text{m}^2 \text{g}^{-1}$ after carbonization and activation. Other bentonite–biochar systems prepared by co-pyrolysis or subsequent modification also show that the clay phase can contribute to a composite architecture with altered micro- and mesoporosity (Yang et al., 2023; Li et al., 2024). The present study uses a simpler formulation and a lower-temperature single-step carbonization, making the magnitude and distribution of the observed surface increase the central experimental result.

Materials and methods. Natural bentonite and wood sawdust were used as the inorganic matrix and carbon precursor, respectively. The experimental series analyzed in this work included only FeCl_3 , NiCl_2 , and CoCl_2 ; no aluminum, zinc, or other metal chlorides were included in the reported data set. Four materials were evaluated: raw bentonite (B0); bentonite–sawdust with 0.75 g CoCl_2 (B-Co); bentonite–sawdust with 0.50 g FeCl_3 (B-Fe); and bentonite–sawdust with 0.50 g NiCl_2 (B-Ni). The catalyst masses are the nominal quantities introduced per 2 g of bentonite. No assumption was made about salt hydration beyond the formulas recorded for the samples.

Table 1 — Composition and thermal treatment of the analyzed materials

Code	Bentonite, g	Sawdust, g	Metal chloride	Catalyst, g	Treatment
B0	—	—	—	—	Raw bentonite
B-Co	2.0	1.0	CoCl_2	0.75	80 °C/24 h; 550 °C/1 h, Ar
B-Fe	2.0	1.0	FeCl_3	0.50	80 °C/24 h; 550 °C/1 h, Ar
B-Ni	2.0	1.0	NiCl_2	0.50	80 °C/24 h; 550 °C/1 h, Ar
<i>Note: prepared by the authors from experimental data</i>					

For each composite batch, 2.0 g of bentonite and 1.0 g of sawdust were combined with the prescribed metal chloride. Distilled water was added gradually until the solids formed a uniformly wetted mixture, which was thoroughly homogenized in the crucible. The mixture was dried at 80 °C for 24 h. The dried material was then placed in a furnace and carbonized at 550 °C for 1 h under an argon atmosphere. After the thermal treatment, the material was allowed to cool before textural characterization (Figure 1). Thus, bentonite/sawdust ratio, drying conditions, carbonization temperature, carbonization time, and gas atmosphere were held constant for all three composite formulations; the metal chloride type and nominal amount were the formulation variables.

Nitrogen physisorption measurements were processed with Quantachrome NovaWin software using a Nova Station A instrument. The analytical gas was nitrogen; the instrument reports specify a measurement temperature of 77.35 K, a molecular cross-sectional area of $16.20 \text{ \AA}^2$, and liquid nitrogen density of 0.808 g cm^{-3} . Specific surface area was determined from the multi-point BET treatment. Pore-size parameters were obtained with the BJH adsorption routine reported by NovaWin; the software output also identifies the de Boer thickness calculation and exclusion of pressure tags below $P/P_0 = 0.35$ in the BJH reduction. BET and BJH calculations were interpreted according to the established limitations of gas-adsorption models (Brunauer et al., 1938; Barrett et al., 1951; Thommes et al., 2015).

Only one archived BET/BJH report was available for each of the four materials. Consequently, the numerical comparison is descriptive: no standard deviations,

confidence intervals, or significance tests are reported. The raw bentonite is also not a catalyst-free carbonized bentonite–sawdust control. Accordingly, changes relative to B0 represent the combined effect of incorporating sawdust-derived carbon and carrying out metal-chloride-assisted carbonization; they cannot be assigned exclusively to the catalytic metal. These constraints are retained explicitly in the interpretation.

AI-assisted preparation statement. OpenAI ChatGPT (GPT-5.6 Sol) was used as an auxiliary tool for language editing, organization of the manuscript, literature-search support, and preparation of data visualizations. It was not used to create or alter experimental measurements. The authors remain responsible for verification of the experimental data, citations, scientific interpretation, authorship information, and the final submitted text.



Figure 1 — Preparation and textural characterization route for the bentonite–sawdust composites.
Note: compiled by the authors from the experimental procedure used for the analyzed samples.

Results. The multi-point BET results show a large and consistent separation between raw bentonite and the three carbonized composites. B0 had a specific surface area of $45.836 \text{ m}^2 \text{ g}^{-1}$. In comparison, B-Co, B-Fe, and B-Ni reached 223.915, 248.350, and 233.406 $\text{m}^2 \text{ g}^{-1}$, respectively (Table 2, Figure 2). The absolute gain in surface area was therefore $178.079 \text{ m}^2 \text{ g}^{-1}$ for B-Co, $202.514 \text{ m}^2 \text{ g}^{-1}$ for B-Fe, and $187.570 \text{ m}^2 \text{ g}^{-1}$ for B-Ni. Expressed relative to the untreated mineral, the BET areas were 4.89, 5.42, and 5.09 times higher.

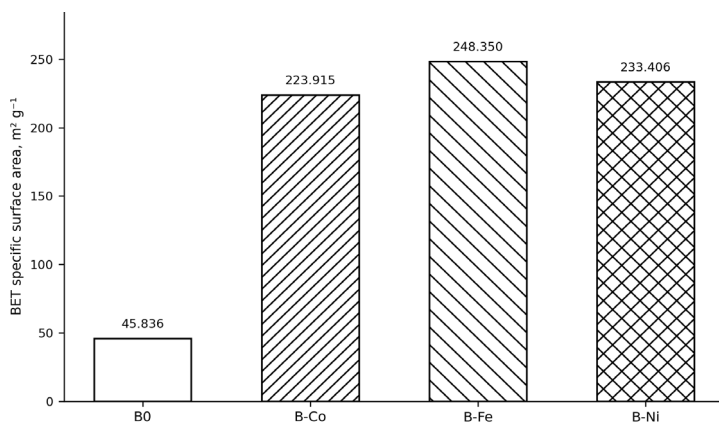


Figure 2 — BET specific surface area of raw bentonite and carbonized bentonite–sawdust composites.

Note: B-Co contains 0.75 g CoCl_2 ; B-Fe and B-Ni contain 0.50 g FeCl_3 and NiCl_2 , respectively, per 2 g bentonite.

The order among the three composite formulations was $\text{B-Fe} > \text{B-Ni} > \text{B-Co}$. B-Ni was 6.0% below B-Fe, and B-Co was 9.8% below B-Fe. The ranking is noteworthy because B-Co contained a larger nominal mass of catalyst than B-Fe or B-Ni, but it should not be converted into a metal-normalized catalytic ranking: the salt formulas recorded for the samples do not specify hydration state, and the composites were not prepared at equal molar metal loadings.

The BJH outputs show a different trend. The adsorption pore volume decreased from $0.012 \text{ cm}^3 \text{ g}^{-1}$ for B0 to $0.008 \text{ cm}^3 \text{ g}^{-1}$ for B-Co, $0.007 \text{ cm}^3 \text{ g}^{-1}$ for B-Fe, and $0.008 \text{ cm}^3 \text{ g}^{-1}$ for B-Ni. The corresponding reductions relative to raw bentonite were approximately 33.3%, 41.7%, and 33.3%. The BJH characteristic pore radius also shifted from $21.517 \text{ \AA}$ (2.152 nm) for B0 to $16.396 \text{ \AA}$ (1.640 nm) for B-Co, $19.552 \text{ \AA}$ (1.955 nm) for B-Fe, and $16.261 \text{ \AA}$ (1.626 nm) for B-Ni. If expressed as characteristic diameters, these values correspond to approximately 4.30, 3.28, 3.91, and 3.25 nm, respectively, all within the mesopore size region.

Table 2 — BET and BJH textural parameters obtained from nitrogen physisorption

Code	BET area, $\text{m}^2 \text{ g}^{-1}$	BJH area, $\text{m}^2 \text{ g}^{-1}$	BJH pore volume, $\text{cm}^3 \text{ g}^{-1}$	BJH pore radius, $\text{\AA}$
B0	45.836	7.718	0.012	21.517
B-Co	223.915	5.285	0.008	16.396
B-Fe	248.350	4.976	0.007	19.552
B-Ni	233.406	5.675	0.008	16.261

Note: values are transcribed from the archived NovaWin reports; one report was available for each material

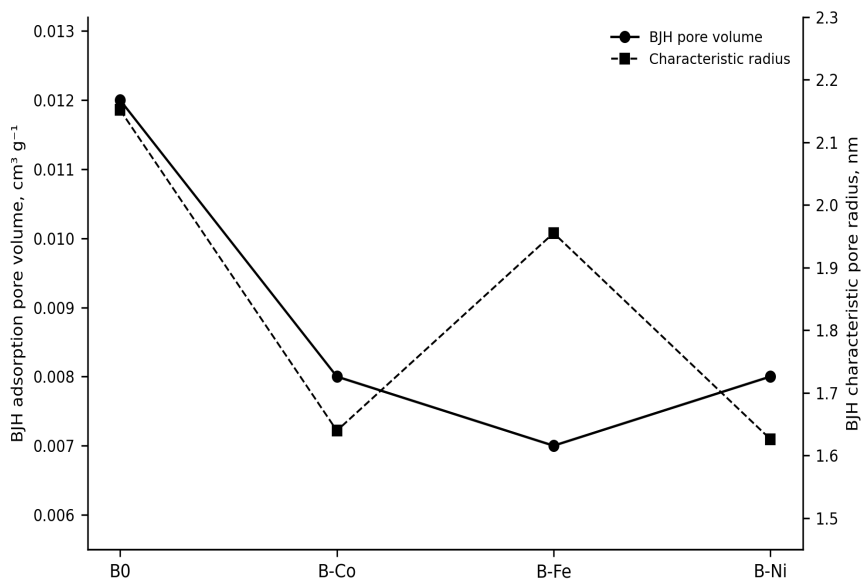


Figure 3 — BJH adsorption pore volume and characteristic pore radius for the four materials.

Note: the plotted pore radii are converted from Å to nm for readability; source values are given in Table 2.

Table 3 — Relative textural change of the carbonized composites versus raw bentonite

Code	$\Delta\text{BET}, \text{m}^2 \text{g}^{-1}$	BET/B0	BET increase	Change in BJH pore volume
B-Co	178.079	4.89	388.5%	-33.3%
B-Fe	202.514	5.42	441.8%	-41.7%
B-Ni	187.570	5.09	409.2%	-33.3%

Note: prepared by the authors from experimental data.

Discussion. The principal experimental observation is not simply that the carbonized materials have larger BET areas; it is the scale of the increase under a moderate 550 °C treatment. A fivefold change from 45.836 to 223.915–248.350 m² g⁻¹ indicates that the carbonization step creates a substantial amount of adsorption-accessible surface that is absent in raw bentonite. This result is consistent with the broader literature on carbon–clay and metal-assisted biomass pyrolysis. Co-pyrolysis of wood with bentonite changes the solid microstructure and thermal evolution of the carbon phase (Wang et al., 2022), while FeCl₃ is known to promote pore development in lignocellulosic carbon precursors (Zhang et al., 2021; Xia et al., 2023). Nickel chlorides and related salts also modify char formation and texture, although the direction and magnitude depend strongly on the anion and process conditions (Hu et al., 2023).

The high BET area does not coincide with an increase in the BJH adsorption pore volume. This apparent contradiction is informative. BJH analysis is primarily used for mesopore-size distributions and does not quantify microporosity with the same reliability as methods based on t-plots, density functional theory, or low-pressure

adsorption analysis (Thommes et al., 2015). The modified samples show lower BJH areas and lower BJH pore volumes than raw bentonite while their BET areas are much larger. A reasonable interpretation is therefore that a substantial part of the newly accessible surface belongs to finer pores outside the dominant BJH mesopore contribution and/or to rough carbon–mineral interfaces generated during carbonization. The present data support this interpretation, but they do not permit a numerical micropore volume to be assigned.

The shift in characteristic BJH radius also indicates that the mesopore population remaining visible to the BJH model becomes finer after carbonization. B-Co and B-Ni show the smallest reported radii, approximately 1.64 and 1.63 nm, while B-Fe retains a somewhat larger characteristic radius of 1.96 nm. In diameter terms, the characteristic values cluster around 3.25–3.91 nm for the composites. The simultaneous presence of a fine mesopore population and a much greater BET area is compatible with a hierarchical texture in which mesopores provide transport paths while finer pores provide much of the surface. A similar combination of clay-derived structure and carbon porosity has been reported in bentonite–biochar composites (Egbedina et al., 2023; Yang et al., 2023).

B-Fe gave the largest BET area, $248.350 \text{ m}^2 \text{ g}^{-1}$, despite containing 0.50 g FeCl_3 compared with 0.75 g CoCl_2 in B-Co. Iron chlorides can promote cracking of lignocellulosic macromolecules, carbon retention, and formation of micropore-rich char, and FeCl_3 has been used specifically to regulate hierarchical pore development (Zhang et al., 2021; Xia et al., 2023). This provides a chemically plausible context for the B-Fe result. It does not, however, prove that FeCl_3 is intrinsically superior to CoCl_2 or NiCl_2 in the present matrix. A rigorous catalyst comparison would require equal molar metal loading, identical hydration states, an uncatalyzed bentonite–sawdust carbonization control, and replicate measurements.

The word graphitization is intentionally avoided as a conclusion from the present data. Fe, Co, and Ni can catalyze graphitic ordering, and the phenomenon is well documented for biomass-derived carbons (Gai et al., 2021; Hunter et al., 2022; Farid et al., 2023). Nevertheless, BET/BJH measurements describe adsorption-accessible texture rather than long-range or nanocrystalline carbon ordering. At 550°C , changes in aromatic condensation may occur, but confirmation of graphitic domains requires Raman D/G-band analysis, XRD, high-resolution microscopy, or another structure-sensitive method. The most defensible description of the current process is therefore metal-chloride-assisted carbonization.

From an application standpoint, a BET area above $220 \text{ m}^2 \text{ g}^{-1}$ makes these composites relevant candidates for later adsorption testing and for evaluation as catalyst-support materials, but surface area alone is not an adsorption capacity or a measure of mechanical strength. Uptake of metal ions or organic solutes will depend on surface chemistry, charge, functional groups, mineral exchange sites, solution pH, and pore accessibility. The present study should therefore be treated as a textural screening stage. Its practical value is the identification of B-Fe as the formulation with the most developed BET surface under the tested conditions, which provides

a rational basis for selecting samples for subsequent XRD/Raman characterization, surface-chemistry analysis, equilibrium sorption experiments, regeneration tests, and mechanical-stability evaluation.

Conclusion. Carbonization of wood sawdust in a bentonite matrix in the presence of FeCl_3 , NiCl_2 , or CoCl_2 produced a pronounced increase in nitrogen-accessible surface at 550 °C. The BET area rose from 45.836 m² g⁻¹ for raw bentonite to 223.915–248.350 m² g⁻¹ for the three carbonized composites, corresponding to approximately fivefold increases. The FeCl_3 -containing formulation had the largest measured area (248.350 m² g⁻¹), followed by NiCl_2 and CoCl_2 . The BET-area increase was accompanied by lower BJH adsorption pore volumes (0.007–0.008 cm³ g⁻¹ compared with 0.012 cm³ g⁻¹ for raw bentonite) and smaller characteristic BJH pore radii. The scientific significance of this result lies in the demonstrated divergence between total BET-accessible surface and the BJH mesopore contribution, which is consistent with a greater contribution from finer porosity and carbon–clay interfaces. The practical outcome is the identification of B-Fe as the priority composition for further development. At the same time, the data do not isolate the catalyst effect from carbon incorporation because an uncatalyzed carbonized bentonite–sawdust control was not measured, and they do not establish graphitic ordering, adsorption capacity, or mechanical strength. These properties require complementary structural, sorption, regeneration, and mechanical tests.

Conflict of interest. *The authors declare that they have no conflict of interest concerning the results presented in this manuscript.*

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