Archives of Environmental Protection
Vol. 51 no. 2 pp. 62–72

PL ISSN 2083-4772
DOI:10.24425/aep.2025.154757

A new ecological mineral-carbonaceous material for adsorption of organic pollutants – a step towards a circular economy

Piotr Słomkiewicz[1]*, Sabina Dołęgowska[1], Katarzyna Piekacz[1], Dariusz Wideł[1], Maria Włodarczyk-Makuła[2]

[1]Institute of Chemistry, Jan Kochanowski University, Kielce, Poland
[2]Faculty of Infrastructure and Environment, Częstochowa University of Technology, Poland

* Corresponding author's e-mail: piotr.slomkiewicz@ujk.edu.pl

Keywords: circular economy, apple pomace, cement dust, biochar, adsorption, fungicide

Abstract: Two industrial waste products – namely, cement bypass dust and apple pomace - were used in the synthesis of a new ecological mineral-carbonaceous material intended that can be used for the adsorption of organic pollutants. The raw materials were mixed at initial ratios of 1:5, 1:9, and 1:18, then subjected to pyrolysis in a nitrogen atmosphere at 800°C. The chemical characterization of the resulting mineral-carbonaceous materials showed that the concentrations of Zn, Cd, and Pb were significantly lower than those in the raw and pyrolyzed bypass dust samples, while the concentrations of Na, Mg, Si, and P were higher. The composition and structure of the mineral-carbonaceous materials depend on the initial dust-to-pomace weight ratio. All materials exhibited a mesoporous nature, with specific surface areas more than one hundred times greater than those of the individual substrates. The highest value exhibits the material with the 1:9 bypass dust-to-apple pomace ratio. This material also had a homogenous, fine-grained structure, with the bypass dust completely covered by carbon.
After 24 h, approximately 90% of captan was removed from the aqueous solution and adsorbed onto the mineral-carbonaceous materials. The removal efficiency depended on the initial bypass dust-to-apple pomace ratio, with the best performance (97.3%) observed in the material synthesized at the 1:9 ratio. Our results confirm that otherwise useless wastes can serve as suitable substrates for the synthesis of mineral-carbonaceous materials, which can function as adsorbents for organic pollutants and as potential sources of valuable nutrients.

Introduction

At present, the reduction of waste generation is at the top of the waste management hierarchy. The European Union places particular emphasis on promoting the sustainable use of resources. According to Communication COM(2005)666, waste should be recycled and reused to minimize its impact on natural resources (Document 52005DC0666es a legal framework for waste prevention, disposal, and recovery, reinforcing the waste hierarchy as a guiding principle (Directive 2008/98/EC).

The concept of the circular economy "*involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible*" (European Parliament, 2023). This approach leads to reduced waste production and the conservation of raw materials. The industrial sector generates a considerable quantity of waste, much of which is not properly managed and ultimately ends up in landfills. The circular economy prioritizes the reuse of waste materials, particularly those with economic value (Pires and Martinho, 2019; Roik et al., 2021; Tamasiga et al., 2022).

Poland is a leading producer of processed apples, with apple pomace accounting for 20–25% of the raw material used in juice and concentrate production. Apple pomace contains dry matter (20%), sugars (7%) and organic acids (about 1%), and essential macronutrients such as calcium, potassium, magnesium and iron. This composition makes it a potentially useful organic fertilizer or animal feed (Barreira et al., 2019; Grasso, 2020; Lyu et al., 2020). Pomace is also characterized by a significant pectin content (about 2%), which can bind heavy metal ions, as well as cellulose, the primary structural carbohydrate in crude fiber. However, its high water content (up to 33%) accelerates fermentation, odor formation, and microbial contamination, posing challenges for storage and management (Kalinowska et al., 2023; Martău et al., 2021). Poland generates approximately 200,000 tons of apple pomace annually, much of which is often disposed of in fields due to a lack of drying infrastructure.

This waste biomass can be successfully converted into a valuable resource, often referred to as "black gold" (biochar), which has potential applications in environmental remediation (Sakhiya et al., 2020; Tu et al., 2022). Its use as a carbon precursor offers an opportunity to recycle organic waste, aligning with the principles of the circular economy and the recent EPA regulations that promote increased organic waste recycling (https://www.epa.gov/.....organics; Tamasiga et al., 2022).

Biochar is a carbon-rich material produced through the thermal decomposition of various biomass sources, including agricultural waste, animal waste, sewage sludge, crop residues, algal biomass, and energy crops (Amalina et al., 2022; Sefatlhi et al., 2024; Vaiškūnaitė, 2024). Its physicochemical properties vary considerably depending on the type of the biomass used and the parameters of the conversion process (Enaime et al., 2020; Nair et al., 2023). A key factor influencing thermal catalysis is the use of inorganic additives, which help stabilize carbon and enrich the final product with valuable nutrients. While mineral doping improves the agricultural and environmental performance of biochar, it also leads to higher production costs due to the expense of the additives (Borek et al., 2023; Buss et al., 2022; Zhong et al., 2023). Therefore, using waste materials as a source of mineral additives offers a more economically and environmentally sustainable alternative.

In this study, the problem of mineral doping was addressed by using an industrial by-product, namely cement bypass dust. A single cement plant can produce up to 1,000 tons of bypass dust per day (Borek et al., 2023; Tkaczewska, 2019). While bypass dust can be reused in cement production, its high chloride content negatively affects the quality of the final product, limiting its direct reuse. However, bypass dust contains high concentrations of valuable elements, including potassium, magnesium, and calcium, making it a potentially valuable source of these elements. Given the challenges associated with its disposal, exploring novel methods for its utilization is crucial for sustainable waste management. (Buss et al., 2022; Uliasz-Bocheńczyk, 2019; Wang et al., 2023).

Despite extensive research on biochar modification using mineral additives, previous studies have primarily focused on the intentional addition of mineral compounds, including potassium- or calcium-bearing minerals (Borek et al., 2023; Buss et al., 2022; Ren et al., 2018), rather than the utilization of waste-based mineral sources. Similarly, while cement bypass dust has been investigated for applications in cement manufacturing, its potential use as a mineral agent in the synthesis of mineral-carbonaceous material remains largely unexplored.

The principal objectives of this study were as follows: (i) to develop, in line with the principles of circular economy, a technology for the production of a new, environmentally friendly mineral-carbonaceous material from two environmentally problematic waste materials, (ii) to characterize the properties of the obtained material, and (iii) to assess its potential use as an adsorbent for captan, a fungicide commonly used in agriculture on a wide range of fruits, vegetables, and ornamental plants.

This research presents an innovative approach using cement bypass dust as a mineral agent in the synthesis of mineral-carbonaceous materials, offering a cost-effective and sustainable alternative to conventional mineral doping methods. Furthermore, this study is the first to investigate the application of this new material for captan removal, addressing a critical gap in pesticide remediation strategies.

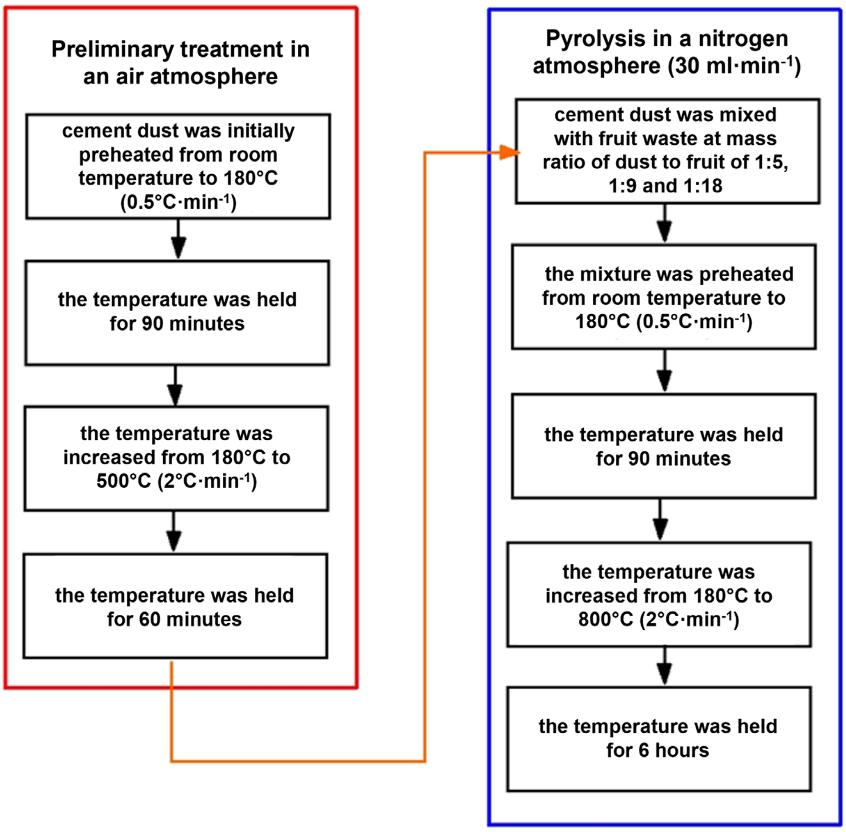

Fig. 1. Step by step synthesis of mineral-carbonaceous materials.

Materials and methods

The elemental and mineral composition of the pyrolyzed apple pomace, raw and preheated bypass dust, as well as the synthesized mineral-carbonaceous materials, were analyzed using (i) wavelength dispersive X-ray fluorescence (WDXRF) (AXIOS, Panalytical) and (ii) X-ray diffraction analysis (XRD) (Empyrean, Panalytical). These techniques provided detailed information on the elemental composition and crystalline phase structure of the materials.

The surface morphology of the substrates and materials was examined using a Zeiss Supra 35 high-resolution scanning electron microscope (SEM), operating at an accelerating voltage of 20 kV with magnifications ranging from 100x to 10 000x. Both secondary electron (SE) and backscattered electron (BSE) detectors were used to obtain comprehensive imaging of surface features and compositional contrasts. Additionally, the surface properties of the materials were characterized using low-temperature nitrogen adsorption-desorption isotherms, measured with a Micromeritics ASAP 2020 analyzer (Norcross, GA, USA). This analysis provided insights into the specific surface area, pore volume, and pore size distribution, essential parameters for understanding the textural properties of the synthesized materials.

Synthesis

The substrates used for the synthesis of mineral-carbonaceous materials included:

– apple pomace, dried at 105°C for 24 hours to remove moisture;
– bypass dust, initially preheated in an air atmosphere at 500°C;

To evaluate the effect of thermal treatment on bypass dust, its elemental and mineral composition was analyzed after preheating at two different temperatures: 500°C and 800°C (Table 1). The results showed that increasing the temperature to 800°C did not cause any significant changes in the elemental or mineral composition of the dust. Based on these findings, and considering the principles of process optimization, bypass dust preheated at 500°C was selected for further studies. The synthesis of mineral-carbonaceous materials was carried out following a controlled experimental procedure. The detailed methodology is described below (Fig. 1):

Captan adsorption experiment

Captan solution was prepared in water at a concentration of 20 mg·L^{-1}, corresponding to typical concentrations used in agricultural applications. A 10 mg portion of the selected material was added to 5 ml of captan water solution. After decantation, a liquid-liquid extraction was carried out using 2 ml of n-hexane.

The n-hexane extracts were analyzed using GC-MS method. The chromatographic analyses were performed on a Clarus 600/600T GC-MS system (Perkin Elmer, USA). An Elite-5MS capillary column (30 m × 0.25 mm × 0.25 µm) was used for the separation. Helium (99.9999% purity) was employed as the carrier gas at a constant flow rate of 2 cm^3·min^{-1}. The injection port was maintained at 250°C and operated in split mode (1:10). A 5 µl sample volume was injected. The ion source and transfer line temperatures were both set to 250°C, and electron ionization was performed at 70 eV. Captan was determined using the following temperature program: 100°C maintained for 1 min, then increased at a rate of 10°C·min^{-1} up to 310°C and held for 9 min. The total analysis time was 31 min. The chromatogram of the captan extract in *n*-hexane and its corresponding NIST database mass spectrum are presented in Fig. 2.

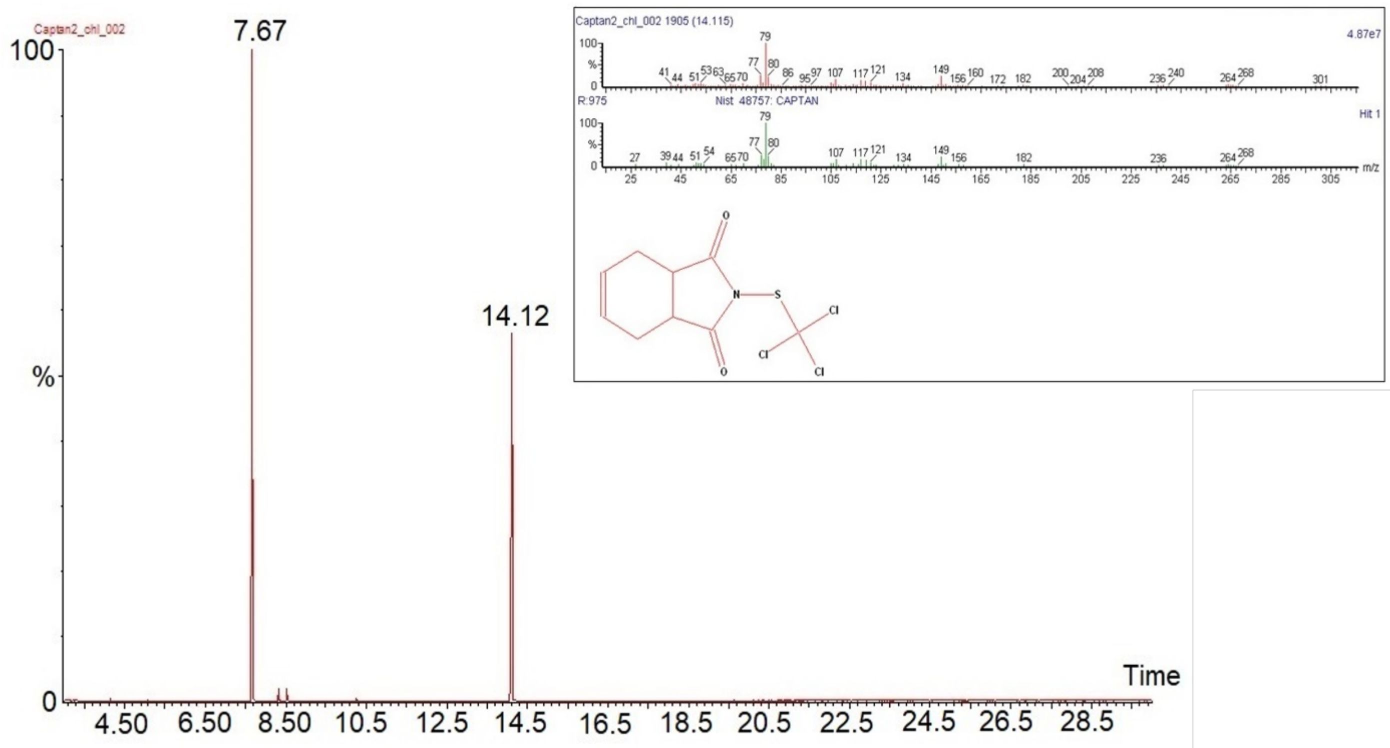

Fig. 2. Chromatogram of captan (retention time 14.12 min) in n-hexane extract; tetradecane as the internal standard at 7.67 min with mass spectrum of captan determined in NIST datebase.

The removal efficiency of adsorbates from the solution (%R) was calculated using Equation (1) (Frydel et al., 2024):

$$R = \left(\frac{C_0 - C_e}{C_0}\right) \cdot 100\ [\%]$$

where: C_0 and C_e represent the initial and equilibrium concentrations of the solution (mg/dm^3), respectively.

Results and discussion

Elemental and mineral composition

Bypass dust, used in the synthesis process as a carrier for active carbon, serves as a source of several elements, including calcium, potassium and sulfur. It also contains considerable amounts of chlorine, cadmium, and lead. The preheating process does not significantly alter its elemental composition, which is consistent with previously published data (Kalina et al., 2022; Qurat-ul-Ain et al., 2021). Nevertheless, samples preheated at a lower temperature (500°C) exhibit slightly higher concentrations of certain elements (Table 1). The elemental composition of the resulting mineral-carbonaceous materials depends on the initial dust-to-pomace weight ratio (Table 1) (Suliman et al., 2016). Regardless of this ratio, the synthesized materials contain significantly lower concentrations of Zn, Cd, and Pb compared to raw and preheated bypass dust samples. In contrast, concentrations of essential elements such as Na, Mg, Si, or P are higher (Table 1). Additionally, a slight decrease in chlorine content further enhances the suitability for these materials for practical applications (Niedziński et al., 2023). These findings confirm the environmental advantages of reusing bypass dust as a substrate in the synthesis of mineral-carbonaceous materials, highlighting its potential as a valuable source of essential nutrients.

The mineral composition of raw bypass dust and bypass dust preheated at two different temperatures (500°C, 800°C) is presented in Fig. 3. The results confirm that these samples can be classified as chlorine-rich materials (Lee et al., 2023). In the raw samples, the potassium chloride content exceeds 40%, increasing to approximately 45% in the preheated samples (Fig. 3). Calcium carbonate accounts for nearly 30% of the raw sample composition (Fig 2A), however, its content decreases by about 6% in samples preheated at 500°C and by 9% in those preheated at 800°C. This decrease is attributed to the gradual decomposition of calcium carbonate at elevated temperatures (Uliasz-Bocheńczyk, 2019). The raw samples also contain potassium sulfate, silicon oxide, calcium hydroxide and oxide, and carbon, with concentrations ranging from 2% (CaO) to 8.2% (K_2SO_4). In the preheated samples, the concentrations range from 3% (CaO, $Ca(OH)_2$) to 14% (K_2SO_4). The observed enrichment in potassium sulfate is likely due to the reduction in the overall mass of the sample during heating, which effectively increases the relative concentration of non-volatile components (Barnat-Hunek et al., 2018; El-Haggar, 2007).

The pyrolyzed pomace is primarily composed of carbon, with only trace amounts of potassium sulfate. These findings align with previously reported results (Amalina et al., 2022; Kane and Ryan, 2022; Niedziński et al., 2023; Tamasiga et al., 2022) and confirm the typical composition of pyrolyzed organic materials under comparable conditions.

Table 1. Elemental composition of bypass dust samples, preheated bypass dust samples and mineral-carbonaceous materials.

Element (%)	Bypass dust	Bypass dust preheated at 500°C	Bypass dust preheated at 800°C	Bypass dust-apple pomace 1:18	Bypass dust-apple pomace 1:9	Bypass dust-apple pomace 1:5
Na	nd	nd	nd	0.095	0.083	0.093
Mg	0.194	0.199	0.181	0.310	0.412	0.474
P	0.034	0.037	0.034	0.594	0.403	0.348
S	4.17	4.38	4.23	3.72	4.37	5.09
Cl	36.7	38.7	36.9	24.7	28.9	26.2
K	11.2	11.9	11.4	10.5	10.6	8.27
Ca	18.0	18.6	17.5	16.8	25.1	26.8
Zn	0.739	0.758	0.749	0.054	0.083	0.103
Cd	4.29	4.02	4.01	nd	nd	nd
Pb	1.23	1.27	1.23	0.181	0.395	0.368

nd - not detected

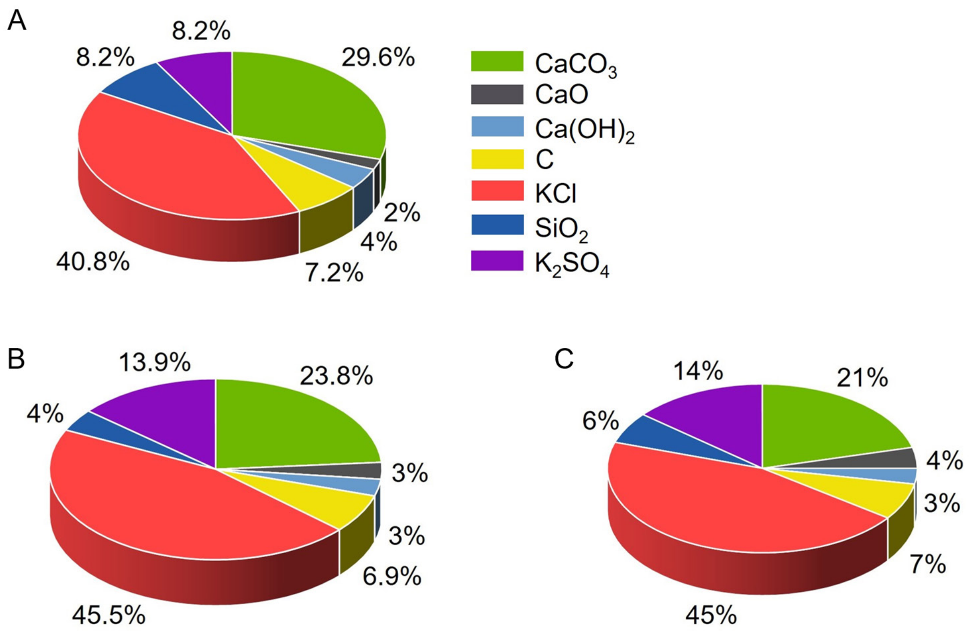

Fig. 3. Mineral composition of: A – bypass dust, B – bypass dust preheated at 500°C, C – bypass dust preheated at 800°C, determined by X-ray diffraction (XRD).

Characteristics of materials

Detailed structural characteristics of the substrates and the obtained mineral-carbonaceous materials are presented in Table 2. The substrates show low specific surface areas (S_{BET}), ranging from 0.54 to 1.27 $m^2 \cdot g^{-1}$, with a relatively small total pore volume, including intraparticle pores. These results confirm that the raw substrates lack the necessary structural properties required for efficient adsorption and, therefore, have limited practical application in sorption processes. In contrast, the specific surface area of the synthesized materials is more than one hundred times greater than that of the individual substrates, ranging from 33.38 to 148.87 $m^2 \cdot g^{-1}$. These differences are strongly influenced by the initial dust-to-pomace ratio, with the highest specific surface area recorded for the material synthesized at a 1:9 ratio. This suggests that this material may possess the most favorable properties as a potential sorbent.

The increase in specific surface area is accompanied by a significant rise in the total pore volume, as well as the proportion of micro- and mesopores, which are critical for adsorption efficiency (Charmas te al., 2024; Gajda et al. 2024). Changing the dust-to-pomace ratio from 1:5 to 1:9 leads to a notable decrease in mesoporosity, exceeding 30%, with the mesopore-to-micropore ratio declining from 4 to 0.94. A further change in this ratio, from 1:9 to 1:18, results in a slight reduction in mesoporosity, from 48 to 42%, and a decrease in the mesopore-to-micropore ratio, from 0.94 to 0.74. The lack of a direct correlation between porosity and specific surface area in our study is primarily due to differences in pore size distribution, structural changes during synthesis, and pore accessibility. The thermal decomposition of apple pomace and its interaction with mineral dust at elevated temperatures leads to heterogeneous pore formation, which affects porosity and surface area independently. Moreover, thee collapse or transformation of mesoporous into microporous can result in higher surface area despite reduced total porosity. These findings highlight the crucial role of the pyrolysis process in transforming low-potential substrates into functional, high-performance sorbents and demonstrate its effectiveness in modifying structural properties to enhance sorption capabilities (Kainth et al., 2024). Moreover, they underscore the importance of optimizing substrate proportions to achieve the best properties of the obtained materials.

The surface properties of the synthesized materials were characterized using low-temperature nitrogen adsorption-desorption isotherms. According to the IUPAC classification, all curves correspond to type IV isotherms (Fig. 4) (Storck et al., 1998). The adsorption isotherms show a gradual increase at low relative pressures, followed by a sharp rise at higher relative pressures (p/p_0), which is typical for mesoporous materials (Table 2) (Charmas et al., 2024, 2023). In all cases, the desorption isotherms run (in the range of $0.5 < p/p_0 < 1$) lie above the adsorption isotherms, suggesting capillary condensation and the presence of hysteresis, another characteristic feature of mesoporous materials (Gommes, Roberts 2018; Tappyrova et al., 2022). The isotherm of the material with the 1:9 initial ratio is higher than those of the other two materials (1:5, 1:18), indicating better surface development (Abin-Bazaine et al., 2022; Toncón-Leal et al., 2021). These results are consistent with the data presented in Table 2, further confirming the superior structural properties of this material.

The bypass dust is characterized by a granular structure, as shown in the SEM image (Fig. 5A), with a relatively low specific surface area of 1.27 $m^2 \cdot g^{-1}$ (Table 2). Heating this material at 800°C has a minimal effect on the porous structure parameters (Table 2), however the porosity appears to be higher (Fig. 5B). The pyrolyzed apple pomace exhibits heterogeneity in grain shape and size (Fig. 5C), along with relatively low values for the porous structure parameters (Table 2). These observations are consistent with previous studies, which indicate that pyrolysis can slightly enhance the porous properties of apple pomace, while the crucial step is associated

Table. 2. Parameters of the porous structure of substrates and obtained materials.

Sample	S_{BET} ($m^2 \cdot g^{-1}$)	V_T ($cm^3 \cdot g^{-1}g$)	V_{mi} ($cm^3 \cdot g^{-1}$)	V_{me} ($cm^3 \cdot g^{-1}$)	Mesoporosity (%)
Bypass dust	1.27	0.0028	0.0016	0.0012	43
Bypass dust preheated at 800°C	1.12	0.0044	0.0019	0.0025	58
Apple pomace pyrolyzed at 800°C	0.54	-	0.00009	-	-
Bypass dust-pomace 1:5	33.38	0.0263	0.0052	0.0210	80
Bypass dust-pomace 1:9	148.87	0.0875	0.0451	0.0424	48
Bypass dust-pomace 1:18	117.86	0.0746	0.0429	0.0316	42

S_{BET} – the specific surface area; V_{mi} – the micropores volume; V_{me} – the mesopores volume; V_t – the total volume of pores and intraparticle spaces determined using methanol filling.

with chemical activation (Suárez-García et al., 2002; Zhang et al., 2022, 2019). The morphology of the synthesized materials (Figs 5D-F) was found to depend on the initial bypass dust-to-pomace ratio as well as on the subsequent pyrolysis conditions (Kalina et al., 2022; Suliman et al., 2016).

The material with a 1:5 initial ratio (Fig. 4D) exhibits a discernible structure that is not entirely covered by the pyrolysate. In contrast, the material with a 1:18 ratio (Fig. 5F) shows a disrupted structure, likely resulting from excessive pyrolysate deposition. Both insufficient substrate coverage and overloading with pyrolysate negatively affect the material's properties and its potential applications as a sorbent. Incomplete coverage decreases material stability and limits pore development, while excessive pyrolysate deposition reduces the available surface area and number of active sites, thereby lowering sorption efficiency. Overloading can also accelerate material degradation, including structural fatigue and other mechanical failures (Charmas at al., 2024; Niedziński et al., 2023; Kalina et al., 2022; Suliman et al., 2016). The material with the 1:9 initial ratio (Fig. 5E) shows the most homogeneous and fine-grained structure, which correlates with its porous structure parameters (Table 2). This highlights the importance of the initial substrate ratio in obtaining materials with the desired properties.

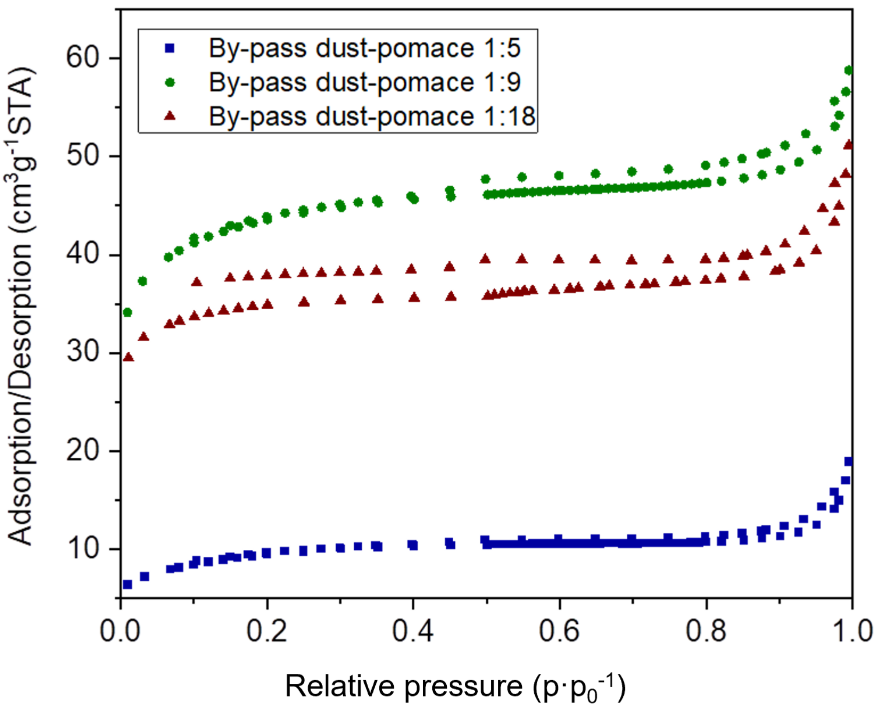

Fig. 4. Adsorption-desorption isotherms for the mineral-carbonaceous materials with different initial substrate ratios.

Adsorption properties of materials in relation to captan

Captan ((3aR,7aS)-2-[(trichloromethyl)sulfanyl]-3a,4,7,7a-tetrahydro-1H-isoindole-1,3(2H)-dione) is a widely used fungicide that has been demonstrated to effectively control numerous diseases in fruits, vegetables, rice and other crops (EPA-738-F99-015, 1999). However, its extensive application has raised environmental and health concerns due to its persistence in soil and water, where it poses a risk of bioaccumulation and potential toxicity. Captan is classified as H351 Category 2 - suspected of causing cancer) under European regulations (https://www.epa.gov/....captan; He et al., 2022).

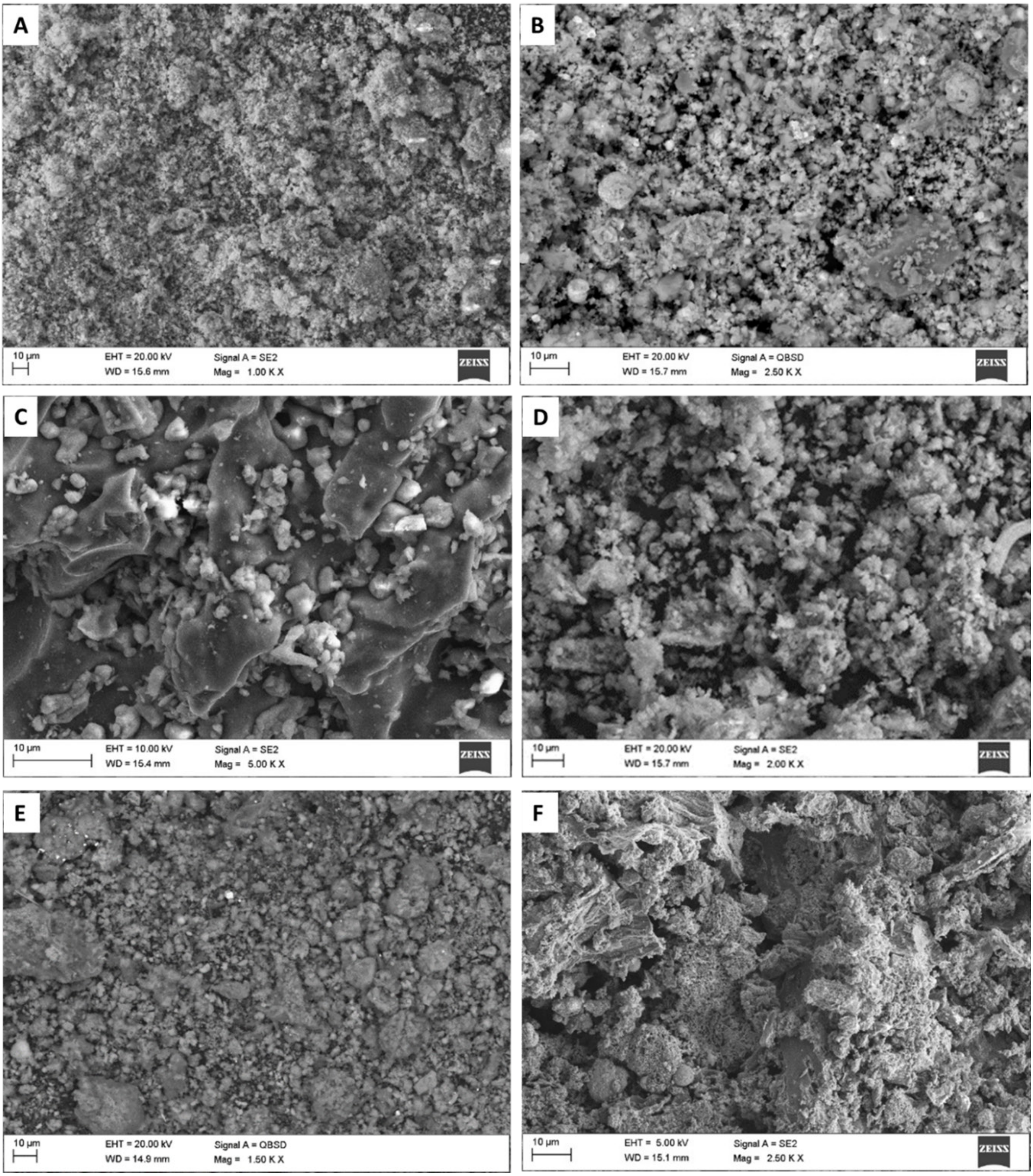

Fig. 5. SEM images: A – bypass dust, B – bypass dust preheated at 800°C, C – apple pomace pyrolyzed at 800°C, D – bypass dust-pomace ratio 1:5 pyrolyzed at 800°C, E – bypass dust-pomace ratio 1:9 pyrolyzed at 800°C, F – bypass dust-pomace ratio 1:18 pyrolyzed at 800°C.

Moreover, overexposure to this pesticide has been linked to potential reproductive toxicity, raising further concerns regarding its long-term environmental and biological impact. Additionally, its metabolite cis-1,2,3,6-tetrahydrophthalimide (THPI), has been reported to exhibit higher acute oral toxicity than captan itself (Bhat et al., 2020; Cutillas et al., 2021), making its removal from the environment particularly crucial.

The removal efficiency of captan by the individual substrates did not exceed 13% (Fig. 6). In contrast, for the mineral-carbonaceous materials, the efficiency after 24 hours ranged from 23.8% to 97.3% (Fig. 6), depending strongly on the initial bypass dust-to-apple pomace ratio. The lowest efficiency was observed for the material with the 1:5 initial ratio. This is likely the result of incomplete pyrolysate coverage, which can lead to the heterogeneity in the sorbent's properties, limiting adsorbent-adsorbate interactions (Ke-fa 2007; Kim et al., 2019). More than 3 times higher efficiency (81.2%), but still lower than the highest result (97.3%), was observed for the material with a 1:18 initial substrate ratio. The reduced efficiency in this case may be attributed to excessive pyrolysate deposition, which can block pores. Blocked pores limit the diffusion of adsorbates, especially larger molecules like phthalates, thereby reducing adsorption capacity (Liu et al., 2016). The highest captan removal efficiency was achieved using the material with a 1:9 initial ratio. This result aligns with the SEM observations and its porous structure characteristics of this material. It further confirms that optimizing the initial substrate ratio in the pyrolysis process is crucial for achieving a balance between effective surface coverage and maintaining high adsorptive properties.

Our findings indicate that the synthesized materials have strong potential for use as captan adsorbents. Moreover, their application does not interfere with the fungicide's intended function but instead helps to prevent excessive contamination of surface soil layers.

Conclusions

In accordance with circular economy principles, two waste materials – cement bypass dust and fruit processing pomace – were repurposed to create a new ecological mineral-carbonaceous material for the adsorption of organic pollutants. The principal findings are summarized below.

The results indicate that apple pomace is a viable source of biochar, and its reuse aligns with directives aimed at increasing recycling of organic waste. Furthermore, the utilization of cement bypass dust as a carbon carrier enables the valorization of a challenging waste material, which typically contains elevated levels of chlorine and trace metals such as Pb, Cd, and Zn. Notably, the concentration of these metals in the synthesized materials was up to 200 times lower than in the raw bypass dust.

The results of SEM analyses indicate that the bypass dust-to-pomace ratio significantly influences the structure of the resulting adsorbents. The materials are characterized by a mesoporous structure with a substantial presence of micropores, and their specific surface area is more than one hundred times greater than that of the individual substrates.

The synthesized adsorbents demonstrate high captan removal efficiency, making them suitable for use in agricultural applications. When applied via spraying, the material effectively fulfills its intended function, with any excess posing minimal risk of contaminating surface soil layers. The low cost of the waste material and the simplicity of the synthesis process, position these mineral-carbonaceous materials as eco-friendly adsorbents for organic pollutants and potential sources of valuable nutrients.

Declaration of interests

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

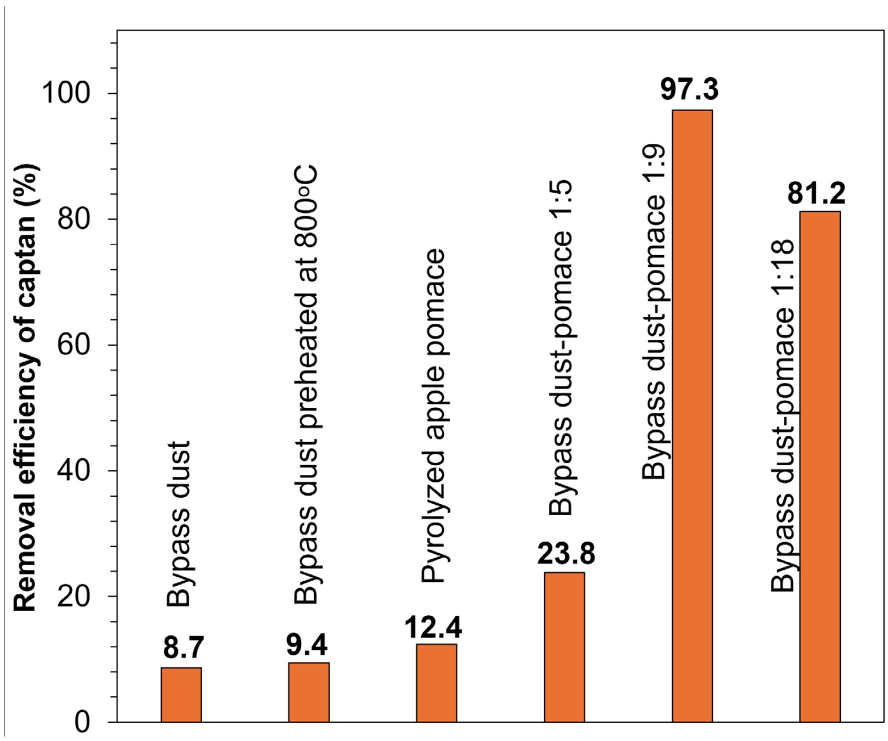

Fig. 6. Removal efficiency of captan v/s different materials.

Funding

This study was supported by the Minister of Science (Poland) under the "Regional Excellence Initiative" program (project no.: RID/SP/0015/2024/01).

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

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Nowy ekologiczny materiał mineralno-węglowy do adsorpcji zanieczyszczeń organicznych – krok w kierunku gospodarki o obiegu zamkniętym

Streszczenie. Dwa odpady przemysłowe, pył cementowy i wytłoki jabłkowe, wykorzystano w syntezie nowego ekologicznego materiału mineralno-węglowego, który może być stosowany do adsorpcji zanieczyszczeń organicznych. Surowce zmieszano w proporcjach początkowych 1:5, 1:9 i 1:18 i poddano pirolizie w atmosferze azotu w temperaturze 800°C. Scharakteryzowano skład pierwiastkowy i mineralny oraz właściwości powierzchniowe za pomocą izoterm adsorpcji-desorpcji azotu w niskiej temperaturze. Właściwości adsorpcyjne kaptanu mierzono metodą GCMS. Charakterystyka chemiczna materiałów mineralno-węglowych wskazała, że stężenia Zn, Cd i Pb w syntetyzowanych materiałach były znacznie niższe niż w surowych i pirolizowanych przez próbki pyłu bypass, podczas gdy stężenia Na, Mg, Si lub P były wyższe. Skład i struktura materiałów mineralno-węglowych zależą od początkowego stosunku wagowego pyłu do wytłoków. Wszystkie materiały wykazywały naturę mezoporowatą, o powierzchni właściwej, która była ponad sto razy większa od powierzchni poszczególnych substratów. Jednak najwyższą wartość wykazuje materiał o stosunku pyłu bypass do wytłoków jabłkowych 1:9. Zaobserwowano, że po 24 godzinach około 90% kaptanu zostało usunięte z roztworu wodnego i zaadsorbowane na materiałach mineralno-węglowych. Wydajność usuwania zależała od początkowego stosunku pyłu bypass do wytłoków jabłkowych, a najlepsze wyniki (97,3%) odnotowano dla materiału o początkowym stosunku 1 do 9. Wyniki naszych badań potwierdziły, że bezużyteczne odpady stanowią odpowiednie substraty do syntezy materiałów mineralno-węglowych, które mogą być wykorzystywane jako adsorbenty zanieczyszczeń organicznych oraz stanowić potencjalne źródło cennych składników odżywczych.