

Article

Influence of Peach Stone Composition, Pretreatment and Processing Method on the Properties of the Resulting Carbon Adsorbent

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Abstract

This paper explores the complex interrelationships between biomass composition, thermochemical conversion pathways, carbon yield and other characteristics in order to expand the knowledge for biomass conversion processes and adapt them to specific requirements. A comprehensive characterization, chemical and thermal analysis of peach stone biomass, was performed. Thermogravimetric analysis, elemental analysis and low-temperature nitrogen sorption were also carried out in order to establish the composition and textural characteristics of the precursor material and obtained product. Carbon adsorbents were obtained from the studied biomass precursor under different conditions via one-step hydro-pyrolysis process by using steam activation at 800 °C. After research was conducted, it was established that cellulose is the main component, which influences the quantity and quality of the obtained adsorbent. The high content of hemicellulose reveals peach stones as a good candidate, especially for hydrothermal carbonization. High cellulose content (40%) in the biomass precursor is a prerequisite for the formation of porous texture in carbon adsorbent during hydro-pyrolysis. It was also shown that the carbon yield (26.70%) can be predicted and is highly dependent on the precursor composition. These results highlight the potential of peach stones as a valuable precursor for the production of sustainable, high-performance carbon adsorbents for environmental remediation.

Keywords: peach stones; thermochemical conversion; carbon adsorbent; circular economy



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1. Introduction

Waste generation has been increasing without control in recent decades, and this has become a global environmental issue [1]. This is also related to the extraction of limited natural resources [2]. To resolve these problems, it is necessary to use secondary materials, which are produced during waste management, as they are the product of sorting and subsequent recycling processes. One of the most effective options to address this problem is recycling. High recycling rates are key to the transition to a circular economy (CE), of which goal is to keep resources in continuous use by creating long-lasting products, inserting them into reusable applications and thus minimizing waste by reusing materials in the

production cycle. Recycling is one way to complete this and represents the essence of a long-term sustainable strategy [3].

The EU countries aim to move from a linear model to a circular economy [4]. According to EUR-Lex (COM/2015/0614), “The transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible and the generation of waste minimised, is an essential contribution to the EU’s efforts to develop a sustainable, low carbon, resource efficient and competitive economy.” The main objectives of the proposed Circular Economy Package are to support the increase in the separation and recycling of waste. The purpose of Directive (EU) 2018/851 is to improve waste management by focusing on waste prevention, reuse and recycling. The circular economy package should help to increase separate collection and recycling, thereby ensuring that valuable materials contained in waste are returned to the economy [5,6].

The production of lignocellulosic waste is mainly due to agricultural and forestry human activities. Approximately 140 Gt of biomass waste is produced globally each year, leading to serious environmental issues [7–10].

About 39% of the total land area in the European Union (EU) is used for agriculture [11], and approximately 23 million tons of dry biomass are produced annually as residual cereal straw [12]. Cellulose- and hemicellulose-rich agricultural biomass waste are valuable raw materials for the production of a wide range of products: chemicals [13], bioactive compounds [14], biomaterials (composites, engineered bioplastics, thermoplastic elastomers, filters and films) [15], supercapacitors [16], carriers for immobilization of enzymes, bacteria and fungi [17], additives [18], biosorbents [19] and biofuels [20,21].

Growing environmental concerns related to industrial pollution, combined with the need for sustainable waste management, have led to the development of efficient, environmentally friendly materials for pollutant removal. Among the most promising materials for such applications are activated carbon adsorbents, distinguished by their high surface area, tunable pore structure and excellent adsorption capacity. Among carbon precursors, lignocellulosic biomass has attracted attention due to its low cost, abundance and renewability [22–25]. Lignocellulosic biomass refers to terrestrial vegetation composed mainly of structural macromolecules: (i) polysaccharides, built up of cellulose, a partially crystalline homopolymer of glucose units, and hemicelluloses, amorphous heteropolymers containing various sugars such as glucose, galactose, mannose, xylose, arabinose, as well as uronic acids and acetyl groups in small proportions, and (ii) lignin, an aromatic amorphous polymer formed by phenylpropane units [26]. Lignocellulosic biomass also contains extractable compounds that can be extracted from the biomass by solvents and are not part of the structure itself [27].

The textural and chemical characteristics of the resulting carbon adsorbent are strongly influenced not only by the thermal treatment parameters but also by the inherent composition of the biomass. Components such as lignin, cellulose and hemicelluloses decompose differently under pyrolytic conditions, and their ratio significantly influences the formation of microporous or mesoporous structures [28–30].

However, the texture and structure of the raw material, which are unique for the different precursors, also have a significant impact on the properties of the final product obtained, especially when using physical activation. This requires, despite the well-studied influence of the individual main components cellulose, hemicellulose and lignin on the properties of the obtained adsorbents to conduct studies to determine the optimal processing conditions for each individual raw material. Due to the specific requirements in some applications of carbon adsorbents such as electrochemistry (production of batteries and supercapacitors, medicine/detoxifiers and chemosorbents), preliminary processing of the raw material is required to achieve the requirements for the final product. Due to the interest shown by the

processing industry, this study seeks optimal processing of peach shells to obtain a carbon adsorbent with appropriate characteristics.

With this study, we set the following goals:

- Determination of the composition of the selected precursor. We focused on peach stones as a precursor, due to their high availability and favorable texture, for the use of physical activation for the preparation of carbon adsorbent.
- Removal of part of the mineral components of the raw material by treating peach stones with hydrochloric acid.
- Changing the chemical composition and texture of the raw material used by extracting peach shells with an organic solvent.
- By one-step steam pyrolysis, produce activated carbon with developed pores texture.
- Determining the influence of the pre-treatment of the raw material on the quality of the obtained carbon adsorbent.

2. Materials and Methods

2.1. Characterization Methods—Raw Materials

Thermogravimetric analysis (TG) and differential scanning calorimetry (DSC) were performed using a STA 449 F3 Jupiter (NETZSCH, Selb, Germany). The instrument is equipped with a built-in high-precision microbalance and supports simultaneous TG/DSC measurements. It is capable of operating in a temperature range from 25 °C to 1400 °C and offers a flexible heating rate range from 0.001 to 50 K/min. Equipped with a built-in high-precision microbalance, the apparatus supports simultaneous measurements with a flexible heating rate and high thermal stability. It offers weighing sensitivity down to 0.1 µg and temperature accuracy of 0.3 µg.

The device is equipped with three sample holders suitable for different types of crucibles, including corundum crucibles (resistant up to 1400 °C), aluminum crucibles (up to 600 °C) and platinum crucibles. A special sample clamp attachment was used for the characterization of liquid samples. All measurements were performed with samples of 10–25 mg under argon atmosphere.

Elemental analysis was performed on a Vario Macro Cube (Elementar Analyzensysteme GmbH, Langenselbold, Germany) apparatus for the determination of C, H, N, S. The oxygen content was determined by difference. Carbon was determined as CO₂, hydrogen was determined as H₂O, while sulfur was determined as SO₂. This system utilizes a precision TCD detector (Elementar Analyzensysteme GmbH, Langenselbold, Germany) to measure gas flow conductivity, with a standard deviation for C, H, N, and S determination of less than 0.1% absolute.

The sample (1–50 mg), covered with tin foil, falls from the autosampler into an oxidation column, where it is heated to 1150 °C in an oxygen atmosphere. After combustion, a gas mixture containing CO₂, H₂O, SO₂ and nitrogen oxides is formed, and the ash remains in a quartz ash tube. The gas mixture passes through a reduction column containing a copper catalyst, which converts nitrogen oxides into nitrogen. The gas mixture then passes through adsorption columns for CO₂, H₂O and SO₂. The remaining nitrogen passes through a precision CVD detector, which determines the gas flow by measuring its conductivity.

Then, CO₂, H₂O and SO₂ are passed one after the other, sequentially, through a CVD detector and measured. Based on these results, the instrument calculates the content (wt%) of N, C, H and S in the sample.

The texture of the synthesized carbon material was characterized by N₂ adsorption at −196 °C, carried out in a Quantachrome Autosorb iQ-C-XR/MP automatic volumetric apparatus (Quantachrome Inc., Boynton Beach, FL, USA). This automatic volumetric apparatus provides pressure measurement accuracy of 0.1% of the full scale, ensuring high

reproducibility in calculating BET surface area and pore volume. Before the experiments, the sample was degassed under vacuum at 350 °C overnight. The isotherms were used to calculate the specific surface area SBET, the total pore volume Vtotal and the micropore volume using the T-plot method [30–32].

The fractures of the studied composite materials were analyzed with a JEOL JSM-6390 (Tokyo, Japan) scanning electron microscope (SEM). Samples with a width of 3 mm and a length of 5 mm were used to observe the fractured surface. The microscope allows for high-resolution visualization down to 3.0 nm, providing a detailed and accurate representation of the pore morphology. The samples were prepared using a sputtering device that applied a 10 Å thick gold layer in the presence of a flow of argon gas. Vacuum pressure was applied to the samples to improve the visualization of the detectors and to obtain representative images of the samples.

The proximate analysis of the biomass and the resulting carbon adsorbents (moisture, ash, volatile matter, and fixed carbon) was performed using a thermogravimetric analyzer STA 449 F3 Jupiter (Netzsch). The procedure followed the ASTM D7582 standard [33] (or equivalent ISO 17246 [34]), employing a heating rate of 10 °C/min up to 900 °C in an inert nitrogen atmosphere, followed by combustion in air to determine the ash content.

Biomass Pre-Treatment and Extraction

Before thermal activation, peach stones were subjected to a chemical extraction process to remove soluble organic and inorganic impurities. Approximately 20 g of dried, ground biomass was treated with 0.1 M hydrochloric acid (HCl) under reflux for 2 h to extract mineral components. The solid residue was then filtered and washed repeatedly with distilled water until a neutral pH was reached.

To further remove tars, oils and surface-bound organics, a Soxhlet extraction was performed using ethanol as solvent for 6 h. The biomass was then dried at 105 °C for 24 h and stored in desiccators before pyrolysis. This two-step pretreatment aims to improve the porosity and homogeneity of the final carbon adsorbent by eliminating volatile fractions that could affect the development of the carbon matrix.

2.2. Preparation of Carbon Adsorbent

The peach shells were obtained from an activated carbon company that uses them as raw material [35].

Activated carbon was prepared by a partial one-step gasification and energy-saving method unlike the commonly used two-stage processing involving carbonization with subsequent activation of the raw material. Samples of 50 g with particle size 1–3 mm were heated in a laboratory installation (vertical stainless steel reactor) in a stream of water vapor (120 mL/min) with a heating rate of 15 °C min^{−1} to a final temperature of 800 °C. The duration of treatment at the final temperature was 1 h. The sample is labeled in the text as carbon adsorbent.

3. Results and Discussion

3.1. Elemental Analysis of PEACH Stones Sample

The data show in Table 1 that the content of carbon has increased from 78.6%, in the carbon adsorbent obtained from the untreated sample, up to 85.2%, in the carbon adsorbent obtained from the treated raw material. At the same time, the oxygen and ash content decreased, which shows successful removal of oxygen functional groups and minerals residues. This enrichment with fixed carbon and the reduction in the mineral components content contributes to improved structural integrity of the obtained carbon adsorbent.

Table 1. Elemental composition of carbon adsorbent obtained from peach stones.

Sample	C (wt%)	H (wt%)	O (wt%)	N (wt%)	S (wt%)	Ash (wt%)
Raw materials	78.6	2.3	10.1	0.99	0.51	7.5
Carbon adsorbent	85.2	2.1	8.0	0.86	1.54	2.3

The decrease in oxygen content from 10.1% to 8.0% suggests a reduction in polar surface groups. This change results in a more hydrophobic and thermally stable surface—favorable for the adsorption of non-polar or gas-phase contaminants. The significant drop in ash content from 7.5% to 2.3% further confirms the effective removal of inorganic impurities by acid leaching, thereby increasing pore accessibility and minimizing pore filling.

3.2. Biomass Composition

Table 2 shows chemical composition data and lignin, cellulose, hemicellulose and lipids content of peach stones, obtained from thermogravimetric (TG) analysis of the agricultural by-product used in this study. Data in Table 2 show that the raw material contains mainly lignin and cellulose. This is important information, as this data is related to the changes that occur in the composition of the raw material during its processing. The relative proportions of cellulose, hemicellulose and lignin critically influence both the thermal decomposition pathway and the structural characteristics of the carbon matrix. Cellulose-rich domains contribute predominantly to pore formation during pyrolysis, while lignin, due to its high thermal stability and aromatic nature, facilitates the formation of a rigid carbon framework with well-developed microporosity.

Table 2. Composition of activated carbon precursor.

Sample	Cellulose, wt%	Lignin, wt%	Hemicellulose, wt%	Lipids, wt%
Raw material	40	37	18	5

The results obtained by this method for the composition of peach stones are similar to those obtained by other researchers using other analysis methods [35].

3.3. Thermal Behavior of Peach Stones Biomass

Thermogravimetric (TG) analysis of the peach stones' precursor revealed a three-stage decomposition profile. The initial mass loss observed below approximately 150 °C was due to the desorption of physically bound moisture. The main decomposition phase, occurring between 250 and 400 °C, corresponds to the thermal degradation of hemicellulose and cellulose fractions. After 450 °C, a gradual weight loss was observed, indicative of the thermal degradation of lignin, a structurally sound and thermally stable biopolymer. The residual mass at the end of the analysis represents the inorganic mineral content (ash) of the biomass.

Differential scanning calorimetry (DSC) measurements show endothermic events associated with moisture evaporation and distinct exothermic peaks corresponding to oxidative decomposition of the organic matrix. These thermochemical transitions offer valuable information on the pyrolysis behavior of biomass and highlight the influence of its lignocellulosic architecture on the evolution of carbon structures during thermal treatment [36].

The TG curve (dashed green—Figure 1) shows three main mass loss events, specifically between 280 and 420 °C, due to the degradation of hemicellulose and cellulose. TG (dashed green) shows peak decomposition rates, while DSC (blue) reveals an endothermic event around 100 °C (moisture loss) and an exothermic peak at approximately 360 °C (oxidative decomposition of volatiles and lignin).

Both samples show (Figure 1 and Table 3) a characteristic endothermic event near 100–110 °C, corresponding to moisture desorption. An exothermic peak is observed at 360 °C

in the untreated sample and at 375 °C in the treated material, reflecting the oxidative decomposition of the organic matrices, especially the lignin-rich fractions. The upward shift in the exothermic peak further supports the structural stabilization achieved by pretreatment.

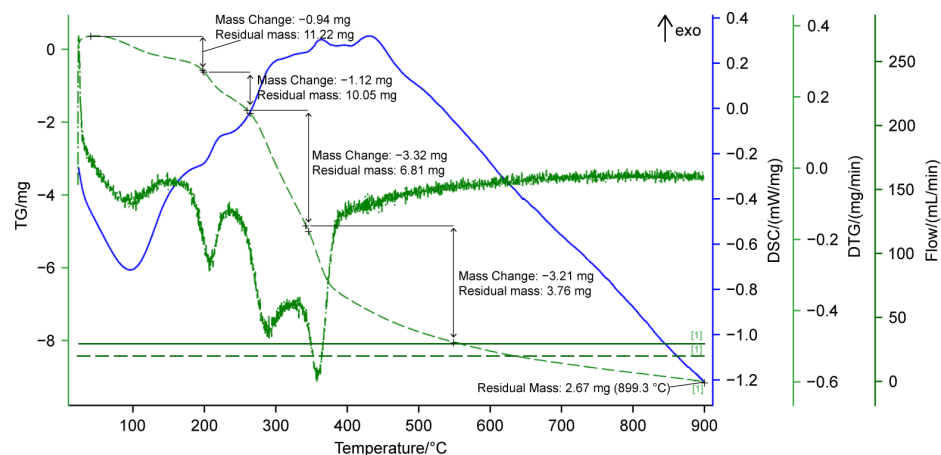


Figure 1. Thermal analysis (TG—DSC) of peach stones (mass change). (dashed green—TG, blue line—DSC).

Table 3. Thermal analysis (TG—DSC) of peach stones (mass change).

Sample	Basic Mass Loss (°C)	Residue at 800 °C (wt.%)	Observed Exo/Endo Events	ΔH J/g
Raw material	280–420 °C	25.6	Endo at 100 °C, Exo at 360 °C	4.827
Carbon adsorbent	290–450 °C	23.8	Endo at 110 °C, Exo at 375 °C	3.793

The residual mass at 800 °C was reduced from 25.6% in the raw biomass to 23.8% in the pretreated sample. This decrease is consistent with earlier data on ash content, confirming the effective removal of inorganics and improved conversion to fixed carbon.

Overall, these findings confirm the role of pretreatment in enhancing the thermal stability of peach stones biomass, thereby facilitating the production of carbon adsorbents with improved structural integrity and purity.

The TG curve (solid green—Figure 2) shows a stepwise mass loss, mainly in the range of 280–420 °C, which is consistent with the degradation of hemicellulose and cellulose. The DTG curve (dashed green) highlights multiple decomposition peaks, while the DSC curve (blue) shows endothermic and exothermic transitions with heat flux areas determined as 4.827 J/g, 3.793 J/g, 0.2373 J/g and 7.035 J/g, indicating various thermal events, including dehydration and combustion of volatiles and carbon fractions.

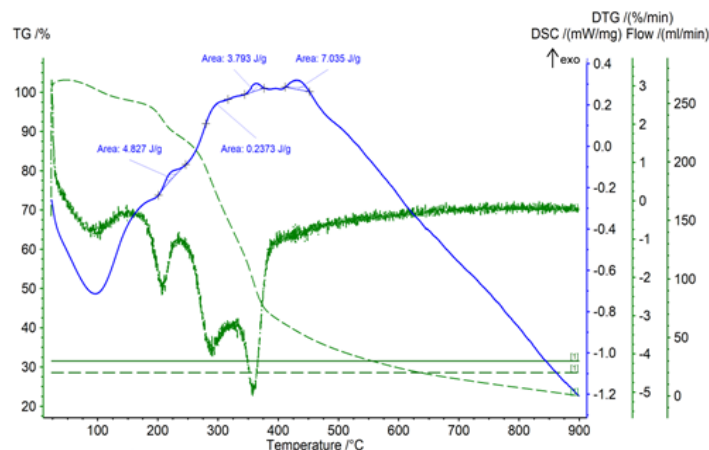


Figure 2. Thermal analysis (TG—DSC analysis) of peach stones (area). (dashed green—TG, blue line—DSC).

3.4. Development of Porous Texture

The processing of the feedstock with a one-step energy-efficient method using steam as a reactant at 800 °C led to the development of a well-defined porous structure [Figure 3]. The nitrogen adsorption–desorption isotherms of the obtained carbon adsorbent showed type I(b) behavior, which is indicative of a predominantly microporous texture. BET analysis revealed a large surface area, while a t-plot confirmed the dominant presence of micropores. DFT pore size distribution showed a narrow peak, which further supports the formation of uniform micropores. The one-step steam activation promotes efficient gas–solid reactions that facilitate the removal of volatile components and the progressive development of the porous texture. This physical activation mechanism allows the generation of a relatively large surface area by the formation and enlargement of micro- and mesoporous structures, without the involvement of chemical activating agents [37–39].

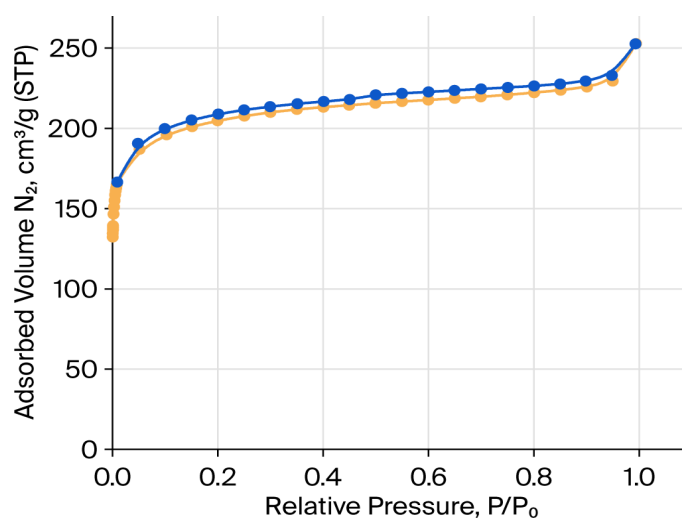


Figure 3. N₂ adsorption isotherms at −196 °C on activated carbon from peach stones. (Adsorption—yellow line, Desorption—blue line).

Comparative Textural Analysis of Carbon Adsorbent Obtained from Untreated and Treated Peach Stones

The comparative evaluation of the carbon adsorbent obtained from untreated and pre-treated peach pits revealed the significant influence of solvent extraction and acid leaching on the development of the pore structure. The pretreated sample showed an improvement in the textural parameters, with the BET surface area increasing from 732 m²/g to 812 m²/g and the total pore volume increasing from 0.45 to 0.58 cm³/g [40,41]. This is a result of the removal of extractable organic substances and mineral impurities during the pretreatment. As a result of this treatment, the contact between the surface released as a result of the pretreatment, and the activating reagent significantly improved, leading to the creation of a more developed porous texture of the obtained carbon adsorbent. The reduction in the ash content from 7.5% to 2.3% confirms the successful elimination of inorganic constituents, such as silicates and metal oxides, by acid leaching. This purification step leads to a decrease in the carbon yield—from 29.4% to 26.7%. The obtained results emphasize the effectiveness of biomass pretreatment to improve the structural and functional characteristics of the carbon adsorbent. Improving the pore texture and increasing the surface area, as well as reducing the content of mineral components, increases the possibilities for applications that require a larger surface area and a negligible content of mineral substances. This is significantly true for applications in medicine and electrochemistry. The obtained results show that the applied pretreatment to improve the composition and texture of the raw material leads to optimization of the properties of the carbon adsorbent obtained

from the treated peach shells. Despite the need for additional treatments, this approach is applicable in cases of specialized applications requiring ultra-high purity or improved pore texture and larger surface area [40,41]. The trade-off between processing simplicity and functional characteristics should be optimized based on the specific requirements of the target application.

Table 4 presents the influence of extraction and subsequent acid leaching on the structural and chemical characteristics of carbon adsorbents obtained from untreated and treated peach stones. The data show better textural parameters of the obtained carbon adsorbent from the pre-treated raw material. After treatment, the surface area measured by the BET method increased from 732 to 812 m²/g, indicating that the removal of volatile tars and inorganic impurities facilitates the development of a more accessible and interconnected pore network.

Table 4. Influence on extraction and subsequent acid leaching on the textural and chemical characteristics of carbon adsorbents obtained from peach stones.

Properties	Carbonization Sample	Carbon Adsorbent
BET surface area (m ² /g)	732.00	812.00
Total pore volume (cm ³ /g)	0.45	0.58
Micropore volume (cm ³ /g)	0.38	0.49
Pore diameter in mode (nm)	1.20	1.10
Carbon yield (%)	29.40	26.70

A similar trend was observed in the total pore volume, which increased from 0.45 to 0.58 cm³/g, along with a remarkable increase in the micropore volume, from 0.38 to 0.49 cm³/g. These changes highlight the role of pretreatment in promoting micropore formation and improving the efficiency of the carbonization process. The slight decrease in pore diameter, in the fashion of 1.2 to 1.1 nm (average), suggests the generation of narrower and more uniform micropores, contributing to a higher degree of surface uniformity.

Therefore, the combined pretreatment strategy significantly improves the surface characteristics and purity of the resulting adsorbent, making it particularly suitable for high-performance applications, such as gas-phase pollutant capture and adsorption of low-molecular-weight organic pollutants.

The effect of pretreatment—including solvent extraction and acid leaching—on the carbon yield and ash content of carbon adsorbents derived from peach stones highlights the inherent trade-off between material purity and production efficiency. Carbon yield shows a modest decrease from 29.4% in the untreated precursor to 26.7% in the treated sample. This decrease is expected, as the removal of extractable organic compounds and mineral matter during pretreatment reduces the total mass retained after pyrolysis. Despite the slight loss in yield, the benefits of improved structural and chemical properties often outweigh the reduction in material performance.

The most pronounced improvement was observed in the ash content, which decreased significantly from 7.5% to 2.3% after acid treatment. This result confirms the efficacy of leaching in eliminating inorganic contaminants such as silicates, carbonates and trace metals. Lower ash content is a desirable characteristic for carbon adsorbents, as it increases chemical purity, improves thermal and oxidative stability and minimizes interference in adsorption processes, especially in sensitive applications such as aqueous phase pollutant removal and gas purification.

In summary, although pretreatment results in a moderately decreased carbon yield, it significantly improves adsorbent quality by reducing ash content and promoting micropore development. This is consistent with the strategic goal of optimizing adsorbent performance for high-value applications where functionality and surface cleanliness are paramount.

3.5. Proximate Analysis of Peach Stones Carbon Adsorbent

The conversion of peach stones biomass into activated carbon significantly changes its proximate composition, reflecting the thermal decomposition and purification processes—see Figure 4. After hydrolysis at 800 °C, the moisture content decreases from 7.2% in the raw material to 3.4% in the steam-activated sample and further to 2.7% in the chemically pre-treated version. This reduction in hygroscopicity is indicative of improved thermal stability and extended shelf life of the final adsorbent.

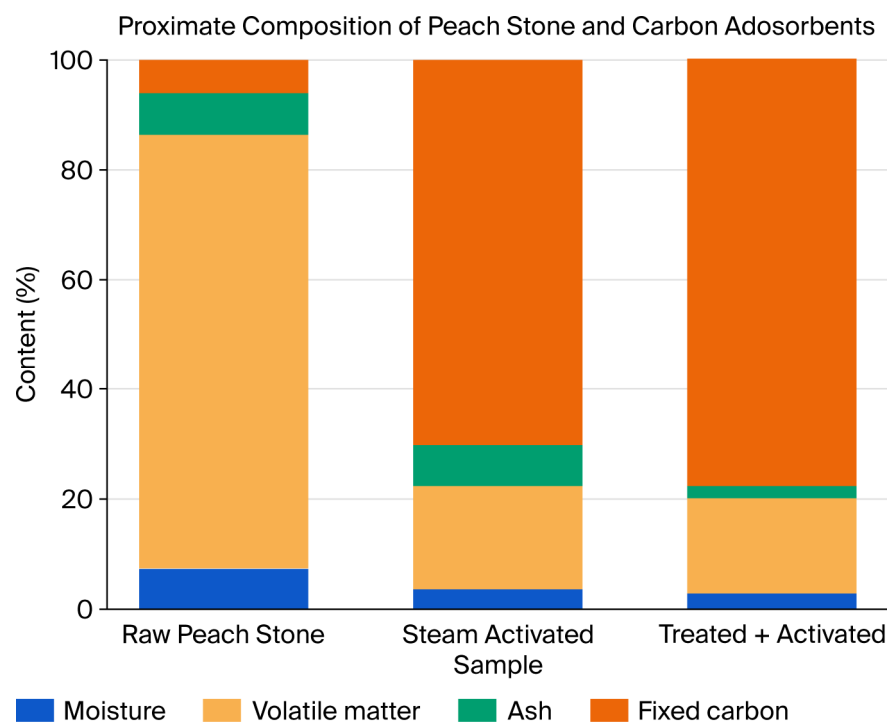


Figure 4. Approximate composition of peach stones and carbon adsorbent.

The volatile matter content also showed a significant decrease, falling from 79.3% in the raw biomass to 18.9% and 17.3% in the steam-activated and treated samples, respectively. This decrease is attributed to the decomposition of thermally labile components such as hemicellulose and cellulose, which facilitate the formation of a stable carbon matrix and the development of porosity.

The ash content remained relatively high (7.5%) in the steam-activated sample, probably because of the presence on residual inorganic substances, the relative proportion of which increases as a result of pyrolysis and loss of organic mass. However, acid leaching during pretreatment effectively reduced the ash content to 2.3%, confirming the successful removal of mineral impurities that could obstruct access to the pores or interfere with adsorption processes.

Therefore, the fixed carbon content increased from 70.2% in the untreated sample to 77.7% in the treated product, highlighting an improvement in the yield of carbon material suitable for adsorption. These findings confirm the role of pretreatment in enhancing not only the chemical purity but also the functional properties of carbon adsorbent derived from lignocellulosic biomass.

Table 5 presents the results of the Soxhlet extraction of carbonized material obtained from peach stones, which revealed approximately 12.4% total extractable content, consisting of 9.8% maltenes and 2.6% asphaltenes. The remaining 87.6% of the material was classified as free carbon, indicative of a highly condensed, thermally stable, and carbon-rich matrix resulting from efficient pyrolysis.

Table 5. Group composition of Soxhlet extraction of carbonized material obtained from peach stones sample.

Component	Content (%)	Description
Maltenes	9.8	Light compounds (saturated, aromatic, resins), soluble in n-hexane or toluene
Asphaltenes	87.6	Remaining solid carbon matrix after extraction
Free (non-extractable) carbon	87.6	Remaining solid carbon matrix after extraction
Total extractables	12.4	Combined maltenes and asphaltenes

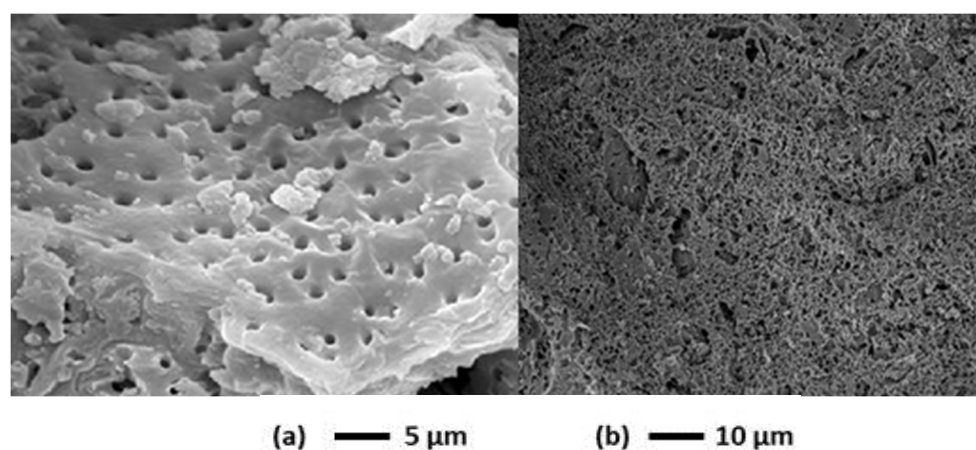
Note: Solvent system used n-hexane followed by toluene in a Soxhlet apparatus; results are based on the weight of the dried sample.

Furthermore, the presence of squalene and other triterpenoid compounds indicates retention of bioactive or lipid-based substances originally present in the peach stone biomass. These findings highlight the potential for utilizing the extractable fraction as a secondary product stream, providing opportunities for the extraction of bio-oils and fine chemicals, along with the production of carbon adsorbent.

The chemical nature of the extractable substances also offers insight into the pyrolytic transformation pathways of lignocellulosic materials and the role of precursor composition in determining the characteristics of the final product.

3.6. Scanning Electronic Microscopy (SEM)

Figure 5 shows SEM micrographs of activated carbon obtained from peach stones. SEM micrographs show that the obtained carbon adsorbent is characterized by the presence of well-developed pores, which is due to the processing method of the raw material and its composition. The SEM data are consistent with the pore distribution data from nitrogen physisorption.

**Figure 5.** SEM micrograph of a peach stones sample (a) and obtained activated carbon (b).

4. Conclusions

This study confirms the potential of peach stones biomass as a viable precursor for the production of highly efficient carbon adsorbents. When using steam activation, the resulting materials demonstrate a well-developed microporous structure and significant BET surface area, characteristics that are critical for applications in environmental remediation.

Pretreatment of the raw material affects the characteristics of the resulting carbon adsorbent (BET surface area 732–812 m²/g, total pore volume 0.45–0.58 cm³/g, micropore volume 0.38–0.49 cm³/g, carbon yield 29.40–26.70%).

Physicochemical properties of the final carbon products are strongly influenced by pre-processing and by inherent composition of biomass from peach stones—in particular, the relative content of lignin, cellulose and hemicellulose. Thermal analysis highlights the characteristic multi-step decomposition of lignocellulosic precursors, while low-temperature nitrogen physisorption reveals the formation of predominantly microporous texture as a result of steam activation.

These results contribute to expanding the possibilities for obtaining the base of peach stones with the application of physical activation of carbon adsorbents with a low content of mineral components and a developed porous texture.

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Institutional Review Board Statement: This study was conducted in accordance with the European Code of Conduct for Research Integrity and the Declaration of Helsinki and according to the rules established by the Ethics Committee of the Institute of Organic Chemistry with Centre of Phytochemistry, Bulgarian Academy of Sciences (protocol code IOCCP-005 and date of approval 23 April 2019).

Informed Consent Statement: Informed consent was established between all the authors and subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jekria, N.; Daud, S. Environmental Concern and Recycling Behaviour. *Procedia Econ. Financ.* **2016**, *35*, 667–673. [CrossRef]
2. Hofmann, M.; Hofmann, H.; Hagelüken, C.; Hool, A. Critical raw materials: A perspective from the materials science community. *Sustain. Mater. Technol.* **2018**, *17*, e00074. [CrossRef]
3. Ordoñez, J.; Harder, R.; Nikitas, A.; Rahe, U. Waste sorting in apartments: Integrating the perspective of the user. *J. Clean. Prod.* **2015**, *106*, 669–679. [CrossRef]
4. Kalmykova, Y.; Sadagopan, M.; Rosado, L. Circular economy—From review of the theories and practices to development of implementation tools. *Resour. Conserv. Recycl.* **2018**, *135*, 190–201. [CrossRef]
5. Stoeva, K.; Alriksson, S. Influence of recycling programmes on waste separation behavior. *Waste Manag.* **2017**, *68*, 732–741. [CrossRef]
6. The European Union. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste. *Off. J. Eur. Union* **2018**, *150*, 109–140. Available online: <https://eur-lex.europa.eu/eli/dir/2018/851/oj/eng> (accessed on 20 November 2025).
7. Agegnehu, G.; Srivastava, A.K.; Bird, M.I. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Appl. Soil Ecol.* **2017**, *119*, 156–170. [CrossRef]
8. Wang, K.; Remón, J.; Jiang, Z.; Ding, W. Recent advances in the preparation and application of biochar derived from lignocellulosic biomass: A mini review. *Polymers* **2024**, *16*, 851. [CrossRef]
9. Behera, S.S.; Ray, R.C. Solid state fermentation for production of microbial cellulases: Recent advances and improvement strategies. *Int. J. Biol. Macromol.* **2016**, *86*, 656–669. [CrossRef] [PubMed]

10. Afolalu, S.A.; Salawu, E.Y.; Ogedengbe, T.S.; Joseph, O.O.; Okwilagwe, O.; Emeteri, M.E.; Yusuf, O.O.; Noiki, A.A.; Akinlabi, S.A. Bio-agro waste valorization and its sustainability in the industry: A review. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1107*, 012140. [\[CrossRef\]](#)
11. Avitabile, V.; Baldoni, E.; Baruth, B.; Bausano, G.; Boysen-Urban, K.; Caldeira, C.; Camia, A.; Cazzaniga, N.; Ceccherini, G.; De Laurentiis, V.; et al. *Biomass Supply and Uses in the EU*; Publications Office of the European Union: Luxembourg, 2023; p. 11. [\[CrossRef\]](#)
12. Zhang, B.; Li, H.; Chen, L.; Fu, T.; Tang, B.; Hao, Y.; Li, J.; Li, Z.; Zhang, B.; Chen, Q.; et al. Recent advances in the bioconversion of waste straw biomass with steam explosion technique: A comprehensive review. *Processes* **2022**, *10*, 1959. [\[CrossRef\]](#)
13. Takkellapati, S.; Li, T.; Gonzalez, M.A. An overview of biorefinery-derived platform chemicals from a Cellulose and Hemicellulose Biorefinery. *Clean Technol. Environ. Policy* **2018**, *20*, 1615–1630. [\[CrossRef\]](#)
14. Sengupta, S.; Bhattacharya, D.; Mukhopadhyay, M. Bioactive compounds production from vegetable biomass. A Biorefinery Approach (Chapter 12). In *Biorefinery Production Technologies for Chemicals and Energy*; Scrivener Publishing LLC: Beverly, MA, USA, 2020; pp. 241–258. [\[CrossRef\]](#)
15. Machado, M.; Hofmann, M.; Garrido, M.; Correia, J.R.; Bordado, J.C.; Rosa, I.C. Incorporation of lignin in bio-based resins for potential application in fiber–polymer composites. *Appl. Sci.* **2023**, *13*, 8342. [\[CrossRef\]](#)
16. Vijayakumar, M.; Sankar, A.B.; Rohita, D.S.; Rao, T.N.; Karthik, M. Conversion of Biomass Waste into High Performance Supercapacitor Electrodes for Real-Time Supercapacitor Applications. *ACS Sustain. Chem. Eng.* **2019**, *7*, 17175–17185. [\[CrossRef\]](#)
17. Bolan, S.; Hou, D.; Wang, L.; Hale, L.; Egamberdieva, D.; Tammeorg, P.; Li, R.; Wang, B.; Xu, J.; Wang, T.; et al. The potential of biochar as a microbial carrier for agricultural and environmental application. *Sci. Total Environ.* **2023**, *886*, 163968. [\[CrossRef\]](#)
18. Chirakkara, R.A.; Reddy, K.R. Biomass and chemical amendments for enhanced phytoremediation of mixed contaminated soils. *Ecol. Eng.* **2015**, *85*, 265–274. [\[CrossRef\]](#)
19. Gautam, R.K.; Mudhoo, A.; Lofrano, G.; Chattopadhyaya, M. Biomass-derived biosorbents for metal ions sequestration: Adsorbent modification and activation methods and adsorbent regeneration. *J. Environ. Chem. Eng.* **2014**, *2*, 239–259. [\[CrossRef\]](#)
20. Gupta, N.; Mahur, B.K.; Izrayeel, A.M.D.; Ahuja, A.; Rastogi, V.K. Biomass conversion of agricultural waste residues for different applications: A comprehensive review. *Environ. Sci. Pollut.* **2022**, *29*, 73622–73647. [\[CrossRef\]](#)
21. Anca-Couce, A. Reaction mechanisms and multi-scale modelling of lignocellulosic biomass pyrolysis. *Prog. Energy Combust.* **2016**, *53*, 41–79. [\[CrossRef\]](#)
22. Sun, M.; Liu, Y.; Xiang, W.; Zhai, L. Electricity- induced catalytic oxidation of RhB by O₂ at a graphite anode. *Electrochim. Acta* **2015**, *158*, 314–320. [\[CrossRef\]](#)
23. Saini, S.; Chand, P.; Joshi, A. Biomass derived carbon for supercapacitor applications: Review. *J. Energy Storage* **2021**, *39*, 102646. [\[CrossRef\]](#)
24. Singh, K.; Kumar, R.; Kaur, A. Novel hierarchical porous carbon derived from biomass Citrus limetta pulp for high-performance quasi-solid-state supercapacitor electrodes. *J. Energy Storage* **2023**, *71*, 108121. [\[CrossRef\]](#)
25. Liu, Y.; Ma, C.; Wang, K.; Chen, J. Recent advances in porous carbons for electrochemical energy storage. *New Carbon Mater.* **2023**, *38*, 1–15. [\[CrossRef\]](#)
26. Rehman, W.U.; Ma, Y.; Khan, Z.; Laaskri, F.Z.A.; Xu, J.; Farooq, U.; Ghani, A.; Rehman, H.; Xu, Y. Biomass-derived carbon materials for batteries: Navigating challenges, structural diversities, and future perspective. *Next Mater.* **2025**, *7*, 100450. [\[CrossRef\]](#)
27. Quan, C.; Zhou, Y.; Wang, J.; Wu, C.; Gao, N. Biomass-based carbon materials for CO₂ capture: A review. *J. CO₂ Util.* **2023**, *68*, 102373. [\[CrossRef\]](#)
28. Duan, D.; Chen, D.; Huang, L.; Zhang, Y.; Zhang, Y.; Wang, Q.; Xiao, G.; Zhang, W.; Lei, H.; Ruan, R. Activated carbon from lignocellulosic biomass as catalyst: A review of the applications in fast pyrolysis process. *J. Anal. Appl. Pyrolysis* **2021**, *158*, 105246. [\[CrossRef\]](#)
29. Huang, B.; Koh, Y.K. Improved topological conformity enhances heat conduction across metal contacts on transferred grapheme. *Carbon* **2016**, *105*, 268–274. [\[CrossRef\]](#)
30. Gomez-Serrano, V.; Gonzalez-Garcia, C.; Gonzalez-Martin, M. Nitrogen adsorption isotherms on carbonaceous materials. Comparison of BET and Langmuir surface areas. *Powder Technol.* **2001**, *116*, 103–108. [\[CrossRef\]](#)
31. Neimark, A.V.; Ravikovitch, P.I.; Grun, M.; Schuth, F.; Unger, K.K. Pore Size Analysis of MCM-41 Type Adsorbents by Means of Nitrogen and Argon Adsorption. *J. Colloid Interface Sci.* **1998**, *207*, 159–169. [\[CrossRef\]](#)
32. Lopičić, Z.; Avdalović, J.; Milojković, J.; Antanasković, A.; Lješević, M.; Lugonja, N.; Šoštarić, T. Removal of diesel pollution by biochar—Support in water remediation. *Hem. Ind.* **2021**, *75*, 329–339. [\[CrossRef\]](#)
33. ASTM D7582; Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis. ASTM International: West Conshohocken, PA, USA, 2021.
34. ISO 17246; Coal—Proximate Analysis. International Organization for Standardization: Geneva, Switzerland, 2010.
35. Núñez-Decap, M.; Wechsler-Pizarro, A.; Vidal-Vega, M. Mechanical, physical, thermal and morphological properties of polypropylene composite materials developed with particles of peach and cherry stones. *Sustain. Mater. Technol.* **2021**, *29*, e00300. [\[CrossRef\]](#)

36. Sandu, T.; Chiriac, A.L.; Tsyntsarski, B.; Stoycheva, I.; Caprarescu, S.; Damian, C.M.; Iordache, T.V.; Patroi, D.; Marinescu, V.; Sarbu, A. Advanced hybrid membranes for efficient nickel retention from simulated wastewater. *Polym. Int.* **2021**, *70*, 866–876. [[CrossRef](#)]
37. Brunauer, S.; Emmett, P.H.; Teller, E. Adsorption of gases in multimolecular layers. *J. Am. Chem. Soc.* **1938**, *60*, 309–319. [[CrossRef](#)]
38. Rouquerol, F.; Rouquerol, J.; Sing, K. *Adsorption by Powders and Porous Solids*; Elsevier: Amsterdam, The Netherlands, 1999. [[CrossRef](#)]
39. Marsh, H.; Rodríguez-Reinoso, F. *Activated Carbon*; Elsevier: Amsterdam, The Netherlands, 2006. [[CrossRef](#)]
40. Lua, A.C.; Yang, T. Characteristics of activated carbon prepared from pistachio-nut shell by zinc chloride activation under nitrogen and vacuum conditions. *J. Colloid Interface Sci.* **2005**, *290*, 505–513. [[CrossRef](#)]
41. Ioannidou, O.; Zabaniotou, A. Agricultural residues as precursors for activated carbon production—A review. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1966–2005. [[CrossRef](#)]

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