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THE EFFECT OF PHOSPHORIC ACID (H_3PO_4) ACTIVATION TEMPERATURE AND TIME ON THE CHARACTERISTICS OF ACTIVATED NANOCARBON BASED ON OIL PALM BIOMASS WASTE THROUGH PYROLYSIS

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Abstract

This study examines the effects of phosphoric acid (H_3PO_4) activation temperature and time on activated carbon from oil palm empty fruit bunches and palm kernel shells through pyrolysis. Dry feedstocks were combined at a 1:1 ratio and pyrolyzed at 450 °C for 120 minutes. Activation at 80, 90, and 100 °C for 90, 120, and 150 minutes was followed by sonication and drying. Characterization comprised carbon yield, moisture content, iodine adsorption capacity, and Particle Size Analyzer (PSA) measurements. Reported yields were 35.9% for empty fruit bunches and 45.7% for shells. Moisture content across nine treatments ranged from 2.05–4.14%, with the minimum at 100 °C for 120 minutes. Iodine adsorption ranged from 870.08–1,150.82 mg/g, reaching its maximum at 100 °C for 150 minutes. These values fell within the moisture and iodine benchmarks in SNI 06-3730-1995. PSA indicated a median of 33.18883 µm and a mean of 48.35910 µm; predominantly nanoscale particles were not achieved. Iodine adsorption increased with activation temperature and time under the tested conditions. Verification of titration procedures, replication, and further characterization are required to strengthen interpretation.

Keywords: activated carbon; oil palm biomass; particle size; phosphoric acid activation; pyrolysis

INTRODUCTION

Oil palm empty fruit bunches (EFB) and palm kernel shells (PKS) are biomass feedstocks that can serve as precursors for carbon materials. Both contain lignocellulosic components that undergo changes during heating, offering opportunities to convert waste into products with added value. Maslahat et al. (2022) investigated EFB as a feedstock for activated carbon, while Aziz et al. (2017) examined shell-derived carbon as a functional material. Such development requires process control to obtain products with characteristics suited to their intended applications.

Carbonization through pyrolysis produces solid carbon that can subsequently be activated to improve adsorption performance. In this study, phosphoric acid (H_3PO_4) was used for activation, with heating temperature and duration as the treatment variables. These variables concern both the duration of contact between carbon and the activating agent and the thermal conditions during processing. Studies by Diharyo et al. (2020) on activation duration and particle size, and Riyanto et al. (2020) on activation temperature and time, establish the relevance of controlling process parameters when characterizing activated carbon.

This study aims to examine the characteristics of EFB- and PKS-derived activated carbon following pyrolysis and H_3PO_4 activation. The observed parameters comprise carbon yield, moisture content, iodine adsorption capacity, and particle size. The objective of producing nanoscale material is evaluated using Particle Size Analyzer (PSA) measurements. Achievement of that objective is therefore assessed from characterization results rather than inferred solely from the grinding and sonication procedures employed.

Using a mixture of EFB and PKS provides a research context distinct from using a single biomass feedstock. Although both originate from the same industry, their physical properties and composition can influence carbon formation during pyrolysis. Information on the yield of each feedstock is therefore needed to interpret carbonization outcomes. During activation, observations focus on changes in carbon characteristics across nine combinations of temperature and time. This approach permits examination of treatment trends within the range of conditions tested.

The main research questions concern how increasing activation temperature and time relates to moisture content and iodine adsorption, and whether the sequence of grinding, sieving, and sonication produces predominantly nanoscale particles. These questions require separate consideration because high adsorption capacity does not itself demonstrate small particle size. Adsorption testing and particle size measurements provide different information and are therefore used together to assess the material.

LITERATURE REVIEW

Oil palm biomass as a carbon feedstock

EFB is a fibrous biomass containing cellulose, hemicellulose, and lignin. These components make EFB a relevant carbon feedstock for thermal processing. Maslahat et al. (2022) examined EFB as a precursor for activated carbon microparticles. The use of other biomass, such as cassava peel in Maulinda et al. (2015), demonstrates that various wastes can be used to develop carbon materials. Nevertheless, each product must be evaluated by testing the material actually produced, because differences in precursors and treatments limit generalization.

PKS has a harder structure than fibrous biomass and can also serve as a carbon source. Aziz et al. (2017) investigated activated carbon from PKS as a supercapacitor electrode material. Their study indicates that the same feedstock can be developed for different functions following processing and characterization. In the present study, shell utilization is limited to activated carbon preparation and assessment of its basic properties. Electrochemical performance, energy storage capability, and the success of specific applications were not measured.

A dry feedstock ratio of 1:1 was used to prepare the EFB and PKS mixture for pyrolysis. This ratio was maintained as a fixed process condition; the study therefore does not compare different mixture compositions. Changes in moisture content and iodine adsorption are consequently discussed in relation to activation conditions, while the effects of varying the feedstock ratio lie outside the experimental scope. Distinguishing fixed conditions from treatment variables is necessary to keep the conclusions consistent with the research design.

Pyrolysis and carbon formation

Pyrolysis is the thermal decomposition of organic material under conditions with no oxygen or limited oxygen availability. Its solid product can provide a starting material for activation, while other components are released during heating. Suhendar et al. (2018) examined the characteristics of carbon obtained by coconut shell pyrolysis, while Saputra et al. (2021) employed pyrolysis to process oil palm fronds. Differences in feedstocks and intended products in previous studies must be considered when relating them to the present results. A pyrolysis temperature of 450 °C and a duration of 120 minutes were maintained throughout the study. The results therefore cannot establish the best pyrolysis temperature. Yield describes only the proportion of solid carbon obtained under those conditions. Quality assessment subsequently considers moisture content, iodine adsorption, and particle size because the quantity of carbon produced does not describe all functional properties of the product.

Phosphoric acid activation and adsorption characteristics

Chemical activation involves treating a carbon material with an activating agent to modify its surface characteristics and pore structure. Activator selection is an important process consideration because outcomes depend on the feedstock, heating conditions, and treatment after activation. Mentari et al. (2018) compared functional groups and morphology in oil palm frond carbon activated with phosphoric and nitric acids. Diharyo et al. (2020) examined H_3PO_4 activation duration and shell charcoal particle size in relation to pores and surface area. Kiełbasa et al. (2022) also investigated several activating agents for molasses-derived carbon, emphasizing the need to identify the activator clearly in each procedure.

In the present study, H_3PO_4 was applied after feedstock pyrolysis. The carbon was then heated at the designated temperature and time, allowed to stand, washed to neutrality, and dried. Washing forms part of product preparation after contact with the activator. Consistent washing and drying are necessary to ensure comparability between treatments. Activator concentration was not a comparison variable in the experimental design. Zulfadhli and Iriany (2017) also discussed H_3PO_4 use with another biomass carbon, employing rubber fruit shells as a precursor distinct from PKS. Activation temperature and contact time represent two different aspects of processing. Temperature

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describes the thermal conditions during contact between carbon and solution, while time determines treatment duration under those conditions. Examining both is necessary to identify the combination giving the highest value for a particular response. The combination with the highest iodine adsorption capacity need not be the one with the lowest moisture content. Selection of a process condition must therefore always specify the assessment parameter.

Moisture content and iodine adsorption capacity

Moisture content indicates the proportion of water lost from a sample during drying under the test conditions. This parameter relates to the dryness of the material when weighed and used. Gravimetric measurement is based on the difference in mass before and after drying. For activated carbon, moisture content is one quality parameter, but it cannot replace assessment of ash content, fixed carbon, or adsorption properties. This study uses the maximum moisture content of 15% for powdered activated carbon in SNI 06-3730-1995 as its benchmark (Badan Standardisasi Nasional, 1995).

Iodine adsorption capacity denotes the amount of iodine adsorbed per unit mass of carbon and is expressed in mg/g. The test is used to compare adsorption capacity between treatments. Its value can indicate surface and pore accessibility, but it is not a direct measurement of specific surface area. The iodine number is therefore not converted into surface area or pore volume in this study. The comparison threshold is a minimum of 750 mg/g under SNI 06-3730-1995.

Particle size and the limits of nanocarbon formation

Nanocarbon development requires evidence of particle sizes within the nanometer range. Lubis et al. (2020) and Suhendar et al. (2018) examined coconut-shell-based carbon materials, while Riyanto et al. (2020) studied activated carbon nanoparticles from water hyacinth. Differences in precursors and processing limit direct application of those findings to an oil palm biomass mixture. In this study, particle size was measured by PSA after processing; nanoscale size therefore remains a synthesis objective to be assessed through instrument results. Particle size and pore size are different characteristics. A particle with a micrometer-scale diameter can still contain pores that contribute to adsorption. Conversely, high iodine adsorption capacity does not establish that particle diameters have fallen below 100 nm.

RESEARCH METHODS

Location and experimental design

The study was conducted at the Plantation Cultivation Laboratory, Institut Teknologi Sawit Indonesia, Medan, from September to December 2025. The experiment used three activation temperatures, 80, 90, and 100 °C, and three activation times, 90, 120, and 150 minutes. Combining the two factors produced nine treatment conditions. Pyrolysis temperature and time, feedstock composition, sieve size, and sonication conditions were maintained according to the procedure. The available value for each combination was analyzed descriptively.

Table 1. Combinations of activation temperature and time

Activation temperature (°C)	90 minutes	120 minutes	150 minutes
80	80 °C; 90 minutes	80 °C; 120 minutes	80 °C; 150 minutes
90	90 °C; 90 minutes	90 °C; 120 minutes	90 °C; 150 minutes
100	100 °C; 90 minutes	100 °C; 120 minutes	100 °C; 150 minutes

Materials and equipment

The main materials were EFB and PKS. Supporting materials comprised phosphoric acid, distilled water, iodine solution, sodium thiosulfate, and starch for titration analysis. Equipment included a pyrolysis reactor, sonicator, oven, blender, 200-mesh sieve, hot plate, analytical balance, desiccator, glassware, pH measurement device, and filter paper. PSA was used to characterize the particle size distribution of the selected sample. This equipment supported preparation, thermal processing, activation, drying, and product analysis.

Feedstock preparation and pyrolysis

EFB and PKS were chopped to approximately 2 cm and sun-dried for three days until dry at constant mass. The dry feedstocks were prepared at an EFB-to-PKS mass ratio of 1:1. The mixture was placed in the reactor and

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pyrolyzed at 450 °C for 120 minutes. The resulting carbon was removed and cooled, then ground in a blender and passed through a 200-mesh sieve to obtain a more uniform fraction.

Grinding and sieving preceded activation to make the carbon easier to contact with the solution. These steps were not used to establish nanoscale size because the size limit associated with sieving differs from a PSA measurement. The masses of dry feedstock and pyrolysis-derived carbon were recorded to calculate yield. EFB and PKS yields are presented according to the records for each feedstock, whereas moisture and iodine results are presented by activation temperature and time combination.

Chemical activation

A 30 g portion of carbon was contacted with 100 mL of 10% H_3PO_4 solution and heated on a hot plate at one of the treatment combinations in Table 1. After heating, the mixture was allowed to stand for 24 hours at room temperature. The carbon was washed repeatedly with distilled water to a neutral pH of approximately 7 and separated using filter paper. The washed solid was dried at 90 °C for 120 minutes. This sequence constituted the activation stage before sonication.

Sonication and final drying

Activated carbon was mixed with distilled water at a 1:10 mass-to-volume ratio to form a suspension. The mixture was then sonicated at 42 kHz for 30 minutes. After sonication, the suspension was allowed to stand for 24 hours at room temperature and then filtered. The solid was washed again to neutrality and oven-dried at 105 °C for three hours. The dry product was stored in a desiccator before characterization. This stage was intended to support particle size reduction and dispersion after activation.

Carbon yield and moisture testing

Yield was calculated as the mass of carbon obtained from pyrolysis divided by the dry feedstock mass, multiplied by 100%. Calculations used the EFB and PKS mass data recorded separately. This parameter describes carbonization yield and is not used to represent the final activated carbon yield after activation, washing, sonication, and filtration. A complete mass balance for all of these stages was unavailable.

Moisture content was determined gravimetrically by sample drying. The test procedure specifies weighing approximately 1 g of carbon in a dish of known mass, drying at 105 ± 5 °C for at least three hours, cooling in a desiccator for approximately 15 minutes, and reweighing. Moisture content was calculated as sample mass loss during drying divided by initial sample mass, multiplied by 100%. Hatibie et al. (2022) also used gravimetric and titration methods as part of carbon characterization.

Iodine adsorption and particle size testing

The iodine adsorption procedure specifies contacting 1 g of carbon with 20 mL of 0.1 N iodine solution for 15 minutes under magnetic stirring. After filtration, a 10 mL portion of filtrate was titrated with 0.1 N sodium thiosulfate. A 1% starch solution was used as the indicator, and titration continued until the blue color disappeared. Iodine adsorption is presented in mg/g according to the results recorded for each treatment. The dilution factor, sample mass, and normality require verification because the worked calculation is not fully consistent with the test procedure.

PSA was performed on one sample selected on the basis of its initial characteristics. The temperature and time combination of this sample was not explicitly identified in the test results, so its distribution is not assigned to any specific one of the nine treatments. Parameters examined included the median, mean, standard deviation, geometric mean, geometric standard deviation, and mode. Instrument statistics were used to describe the size distribution, and the distribution figure is presented as produced by the test.

Table 2. Characterization parameters and assessment criteria

Parameter	Measurement basis	Interpretation limits
Carbon yield	Carbon mass relative to dry feedstock	Pyrolysis output for each feedstock
Moisture content	Mass loss during drying	Compared with the maximum of 15%
Iodine adsorption	Titration after contact with carbon	Compared with the minimum of 750 mg/g

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Parameter	Measurement basis	Interpretation limits
Particle size	PSA statistics and distribution	Size assessment for the selected sample

The data were examined by comparing treatment values and plotting temperature against each response at the three activation times. No significance test is presented because individual replicate data and measures of variability for each treatment are unavailable. Accordingly, the term effect refers to trends observed within the experimental design; it does not imply inferential evidence or establish an optimum beyond the tested range.

RESULTS AND DISCUSSION

Carbon yield after pyrolysis

Pyrolysis produced different carbon yields for EFB and PKS. From 1,000 g of dry feedstock, the recorded EFB carbon mass was 359 g, while PKS produced 457 g. These values correspond to yields of 35.9% and 45.7%, respectively, as shown in Table 3. The difference indicates that the amount of solid carbon obtained under the same pyrolysis conditions depends on the feedstock used.

Table 3. Reported carbon yield for each feedstock

Feedstock	Initial dry mass (g)	Carbon mass (g)	Yield (%)
EFB	1,000	359	35.9
Palm kernel shells	1,000	457	45.7

Pyrolysis at 450 °C for 120 minutes. Yields are reported for each feedstock, not as the final mixture yield after activation.

PKS yield exceeded EFB yield, but this comparison is insufficient to conclude that all characteristics of shell-derived carbon are superior. Yield assesses the proportion of mass retained as carbon, whereas adsorption capacity and particle size require separate testing. Moreover, postactivation output cannot be calculated from pyrolysis yield alone because washing, filtration, and subsequent processing can entail material losses that were not recorded in a complete mass balance.

Characteristics of the nine activation combinations

All moisture and iodine adsorption data for the nine treatment combinations are presented in Table 4. Moisture content ranged from 2.05–4.14%, while reported iodine adsorption ranged from 870.08–1,150.82 mg/g. The table shows that the combination with the lowest moisture content differs from the one with the highest iodine adsorption. The two responses are therefore analyzed separately before being considered together when selecting process conditions.

Table 4. Moisture content and iodine adsorption across nine treatments

Activation temperature (°C)	Activation time (minutes)	Moisture content (%)	Iodine adsorption (mg/g)
80	90	4.14	870.08
80	120	4.09	913.90
80	150	4.03	947.74
90	90	3.61	981.159
90	120	3.26	1,015.44
90	150	3.03	1,049.28
100	90	2.49	1,083.13
100	120	2.05	1,116.98
100	150	2.25	1,150.82

Values follow the experimental data in Appendix A. Decimal precision is preserved as recorded; standard deviations across replicates are unavailable.

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At each activation time, raising the temperature from 80 to 100 °C was associated with lower moisture content and higher iodine adsorption. However, the patterns of change with time were not identical for the two parameters. Moisture content at 100 °C increased between 120 and 150 minutes, while iodine adsorption continued to rise. These differing patterns caution against identifying one condition as best for every product characteristic.

Effects of temperature and time on moisture content

At 80 °C, the recorded moisture contents were 4.14%, 4.09%, and 4.03% for activation times of 90, 120, and 150 minutes. At 90 °C, the corresponding values fell to 3.61%, 3.26%, and 3.03%. When the temperature increased to 100 °C, moisture contents were 2.49%, 2.05%, and 2.25%, respectively. At all three observation times, higher temperature was accompanied by lower moisture content. Figure 1 presents these trends together.

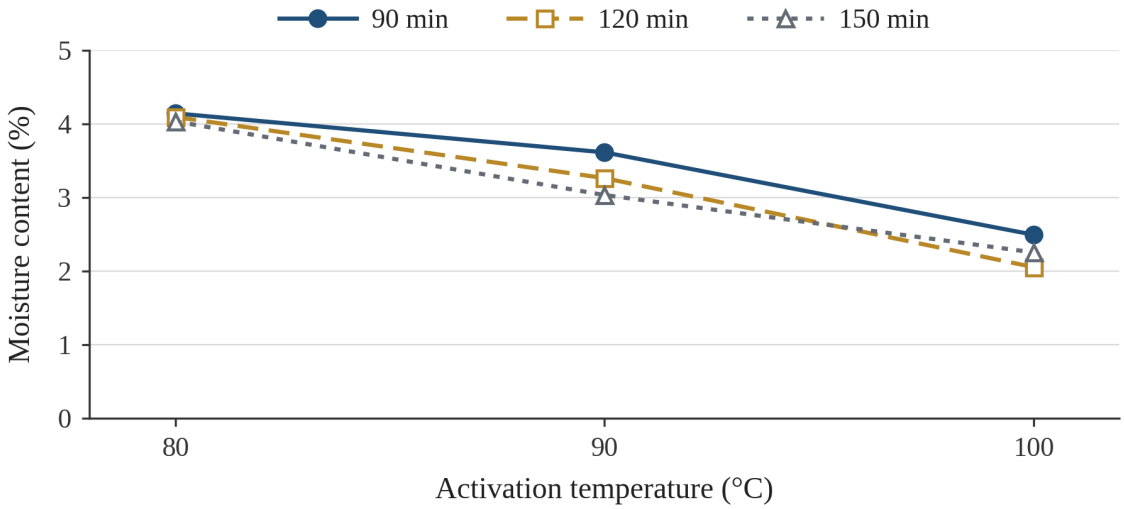


Figure 1. Moisture content at different activation temperatures and times
Points represent reported values; lines connect the tested conditions and do not represent statistical modeling.

The reduction in moisture content is consistent with the role of heating in removing water from the material. Nevertheless, the final value also reflects product conditions after washing, drying, cooling, and storage. The effects of these individual stages were not separated in the experiment. Water removal is therefore offered as a process interpretation, while the magnitude of the observed changes remains grounded in the test values. Moisture content is not used to infer pore distribution or surface area directly.

Moisture content decreased with activation time at 80 and 90 °C. At 100 °C, the minimum occurred at 120 minutes, followed by an increase from 2.05% to 2.25% at 150 minutes. These data show that longer treatment does not always produce lower moisture content. Without replicate information, sample-specific storage conditions, and measurement uncertainty, the cause of this increase cannot be determined. The value of 2.05% is the minimum for one treatment, not the mean of all experiments.

All moisture contents were below the 15% benchmark for powdered activated carbon. This finding supports the assessment that the products were relatively dry when tested. However, meeting one parameter does not establish compliance with all activated carbon quality requirements. The study does not report ash content, matter lost on heating, or all other characteristics needed for a comprehensive assessment against the standard.

For process selection, 100 °C for 120 minutes gave the lowest moisture content among the available treatments. This condition can serve as a reference point for further research prioritizing product dryness. Further assessment still requires replication and control of conditions after activation so that small treatment differences can be distinguished from variation in sample handling.

Effects of temperature and time on iodine adsorption

Iodine adsorption increased with each rise in activation temperature and time within the tested range. At 80 °C, it increased from 870.08 to 913.90 and 947.74 mg/g. At 90 °C, the recorded values were 981.159, 1,015.44, and 1,049.28 mg/g. At 100 °C, adsorption reached 1,083.13, 1,116.98, and 1,150.82 mg/g. The sequence at each temperature corresponds to activation times of 90, 120, and 150 minutes.

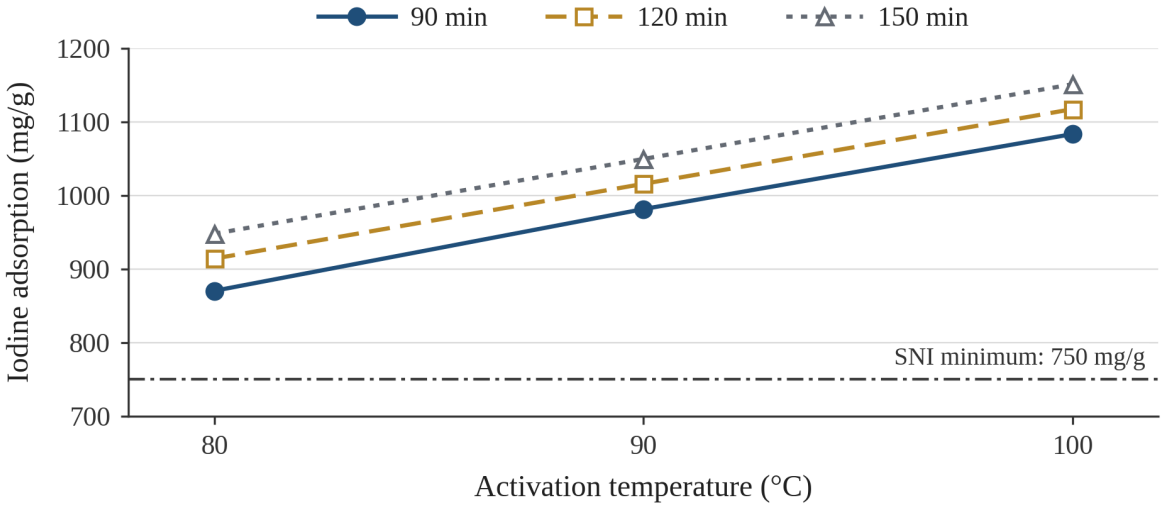


Figure 2. Iodine adsorption at different activation temperatures and times

The reference line marks 750 mg/g. The chart presents tabulated results without error bars because replicate data are unavailable.

The highest value, 1,150.82 mg/g, was obtained at 100 °C for 150 minutes. This combination was the best condition based on the iodine number among the nine available treatments. The result does not establish a mathematical optimum because temperatures above 100 °C and durations beyond 150 minutes were not tested. The term best is restricted to the experimental range and the iodine adsorption response; it is not extended to conclusions about energy efficiency or particle size.

The increase in iodine number can be discussed in relation to changes in surface and pore accessibility after contact with the activating agent. Diharyo et al. (2020) considered H_3PO_4 activation duration as a processing parameter for shell-derived carbon, while Mentari et al. (2018) examined differences in material characteristics associated with activator use. These relationships provide a conceptual basis for interpreting the results, but the mechanism of pore modification in this experiment has not been demonstrated through morphology measurements or gas adsorption.

All reported iodine numbers exceeded the 750 mg/g benchmark. These results indicate adsorption potential according to the test parameter used. However, the procedure records and worked titration calculation still require review. The table values are therefore retained as reported results and are not treated as independently verified from raw titration data. Their use for quality certification or rigorous quantitative comparison first requires consistency in the procedure and calculations.

Iodine adsorption also cannot directly predict the ability to remove particular heavy metals or dyes. Different adsorbates can produce different responses, whereas this study tested iodine alone. Application testing in future research should specify the initial concentration, adsorbent mass, contact time, pH, and appropriate test conditions so that performance for the intended application can be assessed directly.

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Particle size distribution and evaluation of the nanoscale objective

The PSA output gave a median particle size of 33.18883 µm and a mean of 48.35910 µm. The recorded standard deviation was 44.4250 µm, and the mode was 16.2921 µm. The instrument median provides the reference for interpreting D50. These statistics indicate that the selected sample remained within the micrometer size range. Table 5 summarizes the instrument results.

Table 5. Particle size statistics from the PSA output

Parameter	Value	Unit
Median or D50	33.18883	µm
Mean	48.35910	µm
Standard deviation	44.4250	µm
Geometric mean	34.1588	µm
Geometric standard deviation	2.2953	Dimensionless
Mode	16.2921	µm

Statistics refer to one selected sample. Its activation condition is not explicitly identified.

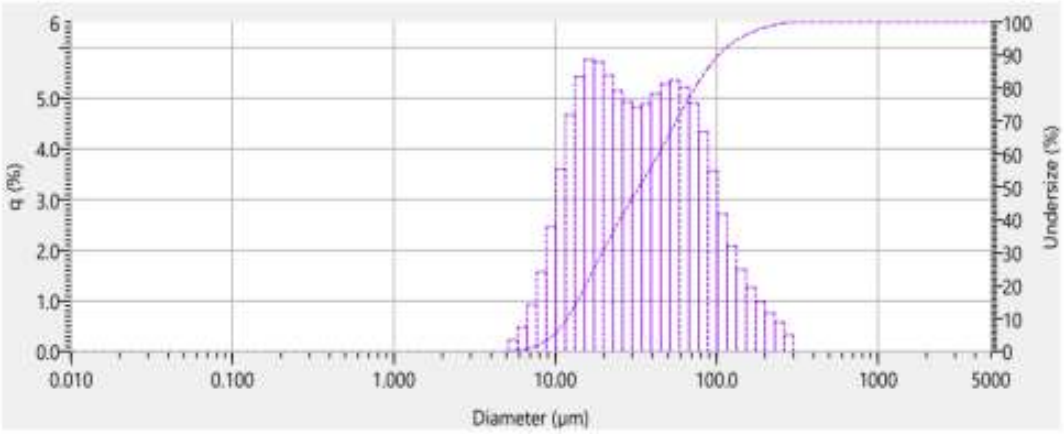


Figure 3. Particle size distribution in the original PSA output

The original instrument image is retained; the diameter axis uses µm. The curves were not reconstructed because size-class data are unavailable.

A mean larger than the median, accompanied by a substantial standard deviation, indicates that a single value cannot adequately represent the size distribution. The graphical output shows particles spanning a relatively broad micrometer range. These data do not support a claim that the product was dominated by particles smaller than 100 nm. Particle distribution must be distinguished from pore distribution; iodine adsorption performance is therefore compatible with PSA results that remain on the microscale.

Blender grinding, 200-mesh sieving, and sonication at 42 kHz for 30 minutes have not provided evidence that the nanoscale objective was achieved. Process improvements could focus on initial size control, dispersion conditions, and the intensity of particle size reduction. However, possible limitations in sonication energy or aggregate formation still require investigation. SEM or TEM analysis is needed to clarify morphology, while BET measurements are required to assess surface area and pore characteristics directly.

Relationships among characteristics and comparison with previous research

The results show that yield, moisture content, iodine adsorption, and particle size provide different information. Yield describes carbonization output, moisture content indicates dryness, iodine assesses the adsorption response, and PSA describes particle size distribution. Carbon with the highest iodine number cannot automatically be considered to have the smallest particles because PSA was not performed for every combination. Process selection should be guided by the characteristic that the intended application requires.

Assessment through several methods is consistent with the range of characterization approaches in the cited literature. Puccini et al. (2017) used adsorption indicators when studying activated carbon from waste-derived

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hydrochar. Bakti et al. (2022) examined coconut shell carbon by XRD and SEM-EDX, while Rahayu et al. (2023) investigated the porosity, texture, and morphology of nipa shell carbon. These references demonstrate the need to align claims about material characteristics with the methods used to measure them. Results from different materials or processes are not treated as direct comparisons without considering their test conditions.

Estimated research costs

The research records include equipment costs of IDR 5,033,000 and material costs of IDR 810,000. Equipment listed at zero cost was provided by the laboratory without new purchases, so the amount does not represent the full investment value of the facilities. Material costs include EFB, PKS, phosphoric acid, distilled water, iodine, and starch. These two cost categories differ in scope from the estimated process components in Table 6 and are not added again to form a combined total.

Table 6. Estimated process cost components listed in the study

Component	Amount (IDR)
EFB and PKS feedstock mixture	1,750
LPG fuel	50,000
Phosphoric acid	500,000
Distilled water	60,000
Electricity	20,000
Iodine solution	140,000
Starch	75,000
Total stated in the report	816,750
Arithmetic sum of the components above	846,750

The final row checks the sum of the components; it is not a newly measured cost. The estimate does not yet use a uniform production mass basis.

Phosphoric acid is the largest component in this estimate. Nevertheless, the activation solution requirement in the method cannot be equated directly with the concentrated phosphoric acid purchase in the cost list. The cost records also use different bases for the feedstock mixture, carbon mass for activation, and estimated washing requirements. The table therefore cannot be used as a production cost per kilogram of final activated carbon.

The discrepancy between the stated total and the sum of the components must be reconciled before extending the economic analysis. A subsequent feasibility assessment requires a consistent calculation basis, a final product mass balance, measured energy demand, chemical consumption, and allocation of facility costs. At this stage, the cost information describes research requirements and does not establish the commercial viability of the product.

Limitations and future development

The main limitations concern the completeness of test documentation and the scope of characterization. Although the design mentions experimental replication, the available results do not include individual replicate values, response standard deviations, or statistical tests. Moisture and iodine trends therefore cannot establish statistically significant effects. Further experiments should record replicate data for every combination and maintain consistent sample handling conditions so that factor effects and measurement variability can be analyzed.

Several process conditions are also documented inconsistently across the procedure, study scope, and flowcharts. Differences concern H_3PO_4 concentration, sonication time, and drying duration after activation. The operational procedure specifies 10% H_3PO_4, 30 minutes of sonication, and 120 minutes of drying after activation, but other parts of the records contain different values. Laboratory records must be consulted before the procedure is used to replicate the study.

The iodine calculation requires particular attention because its worked example uses a sample mass and titrant volume that are not fully consistent with the method description. The iodine values in the table remain the reported results, but their traceability must be strengthened by documenting blanks, normality, dilution factors, carbon mass, and titration volumes. The identity of the sample submitted for PSA must also be linked to a treatment code so that particle size can be compared with moisture content and adsorption response for the same sample.

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Further characterization using SEM or TEM is recommended to examine morphology and particle scale, together with BET analysis to measure surface area and pore characteristics. Particle size reduction, sonication duration, and dispersion conditions can be investigated further, but success must be established through instrument results. Heavy metal or dye testing is also needed if the product is to be developed as an adsorbent. Such applications are directions for future research and have not been demonstrated by iodine testing alone.

CONCLUSION

Pyrolysis of oil palm biomass at 450 °C for 120 minutes produced reported carbon yields of 35.9% for EFB and 45.7% for PKS. After H_3PO_4 activation under nine temperature and time combinations, moisture content ranged from 2.05–4.14%. The minimum moisture content was obtained at 100 °C for 120 minutes. Increasing temperature was accompanied by lower moisture content at each observation time, but extending activation to 150 minutes at 100 °C did not reduce moisture further.

Reported iodine adsorption ranged from 870.08–1,150.82 mg/g, with the highest value at 100 °C for 150 minutes. All moisture and iodine values fell within the respective benchmarks in SNI 06-3730-1995. These results do not establish compliance with every standard parameter or statistical significance between treatments. The titration method and calculations require review to strengthen the validity of the iodine values before further quality assessment.

PSA results showed a median of 33.18883 µm and a mean of 48.35910 µm. The tested product therefore remained dominated by micrometer-sized particles, and the objective of nanocarbon formation was not achieved. Further development should prioritize procedural consistency, experimental replication, size reduction, and morphological and pore characterization. The available cost estimates still require a consistent calculation basis and are insufficient to establish the feasibility of commercial production.

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