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Hierarchically porous carbon derived from agricultural waste as an optimal precursor for materials used in energy storage systems

Omirzak Kapizov[1,2], Zura Yessimsiitova[3]*, Dauren Mukhanov[3,4], Assiya Nuraly[1,5], Aknur Seisenova[1], Kalima Manap[1,2], Akzhunis Akimbayeva[1,4], Alibek Mutushev[1,5]*

1. *Scientific Center for New Technologies; Almaty, Al-Farabi 7k, Nurly Tau Business Center, Block 5A, 334b, 050059, Kazakhstan*
2. *AlAkSan; Al-Farabi 7k, Nurly Tau Business Center, Block 5A, 334b, 050059, Kazakhstan*
3. *Al-Farabi Kazakh National University, 71 al-Farabi Avenue, Almaty, 050040, Kazakhstan*
4. *Center for Advanced Science and Technology, Akkainar Village, Zhambyl District, Almaty Region, Suranshy Batyr Street, House 26, 040602, Kazakhstan*
5. *Department of Chemical and Pharmaceutical Manufacturing Technologies, Almaty Technological University; Almaty, Tole bi st., 100, 050012, Kazakhstan*

* *Corresponding author's Email: alibek_090@mail.ru , zura1958@bk.ru*

ABSTRACT

Hierarchically porous carbon materials derived from agricultural waste are increasingly recognized as sustainable and structurally optimized precursors for advanced energy storage systems. In this work, carbon materials were synthesized from rice husks and fruit kernels via controlled pyrolysis, with the aim of achieving a balanced micro–mesoporous architecture without excessive chemical activation. The resulting carbons preserve intrinsic structural motifs of the biomass, enabling the formation of interconnected pore networks that combine sufficient surface accessibility with mechanical integrity. Nitrogen adsorption–desorption analysis revealed isotherms combining type I and type IV behavior, confirming the coexistence of micro- and mesopores. The specific surface area of the obtained materials was maintained within a moderate range (approximately 70–140 $m^2\ g^{-1}$ for most samples), avoiding the drawbacks associated with highly activated carbons, such as excessive solid–electrolyte interphase formation and low volumetric energy density. The hierarchical pore structure facilitates efficient ion transport through mesopores while providing abundant charge storage sites within micropores. These characteristics make biomass-derived carbons particularly suitable as structural frameworks and precursors for silicon–carbon composites and other electrode materials in lithium-ion, sodium-ion, and supercapacitor systems. The results demonstrate that agricultural waste can be rationally transformed into reproducible, structurally optimized carbon materials, offering a sustainable and effective alternative to highly activated synthetic carbons for next-generation energy storage applications.

Keywords: Hierarchically porous, Carbon materials, Agricultural waste, Energy storage, Silicon-carbon composites.
Article type: Research Article.

INTRODUCTION

Energy storage materials and structural requirements

Electrochemical energy storage systems, including lithium-ion batteries (LIB), sodium-ion batteries (SIB), and supercapacitors, play a key role in modern energy technologies due to their high efficiency, scalability, and compatibility with renewable energy sources (Malik *et al.* 2025). Despite significant progress in the development of active materials, the performance, stability and service life of these devices are largely determined by the structural properties of electrode materials, especially at the nanoscale (Mohammed *et al.* 2025). Among them,

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carbon materials are widely used as conductive matrices, active components or structural supports due to their chemical stability, high electrical conductivity and tunable porosity (Kömür *et al.* 2025). In carbon electrodes, the carbon matrix performs several critical functions. It provides continuous electron transport pathways, maintains structural integrity during repeated charge-discharge cycles, and regulates ion diffusion within the electrode (Li *et al.* 2024). In composite systems such as silicon-carbon anodes, the carbon phase additionally serves as a mechanical buffer, compensating for the significant volume changes of high-capacity materials while suppressing particle agglomeration and electrode destruction (Dou *et al.* 2019). Thus, the characteristics of energy storage materials are determined not only by their chemical composition, but also depend to a large extent on the pore architecture and textural characteristics of the carbon matrix (Li *et al.* 2025). Although high specific surface area has long been considered a favorable factor for electrochemical properties, recent studies have shown that overly activated carbon materials can lead to undesirable effects, including excessive formation of the solid electrolyte interphase (SEI) layer, low volumetric energy density, and deterioration of cycle stability (Gao 2017). In contrast, a hierarchically porous structure combining micro- and mesopores with a moderate specific surface area is increasingly being considered a more effective design strategy (Sun *et al.* 2016). Micropores provide a large number of charge storage centers, while mesoporous promote rapid ion transport and electrolyte penetration while maintaining structural integrity (Merum & Kang 2025). Consequently, rational pore architecture, rather than extremely high specific surface area, is becoming a key structural requirement for carbon materials intended for advanced energy storage systems (Zhang *et al.* 2023).

Limitations of highly activated carbons

Highly activated carbon materials with extremely high specific surface areas have been widely investigated for electrochemical energy storage systems due to the large number of available adsorption sites (Suleimenova *et al.* 2023; Mutushev *et al.* 2025). However, a growing body of experimental and theoretical evidence suggests that excessive activation does not necessarily lead to improved electrochemical performance, especially in battery systems and composite electrodes. On the contrary, excessively high specific surface area can cause a number of internal limitations that negatively affect long-term stability and practical energy density (Asamoah *et al.* 2024; Mutushev *et al.* 2025). One of the main disadvantages of highly activated carbons is their increased surface reactivity towards electrolytes. A large number of defect centers, edge planes and oxygen-containing functional groups contribute to parasitic side reactions during electrochemical cycling, leading to continuous electrolyte decomposition (Wang *et al.* 2018). As a result, an unstable and excessively thick solid electrolyte–electrode interface (SEI) layer is formed, accompanied by the consumption of active lithium or sodium ions and a rapid drop in capacity. This problem is particularly critical for silicon-carbon composite anodes, where interphase stability plays a decisive role in cycling characteristics (Huang *et al.* 2017). In addition, carbon materials with extremely high specific surface areas are often characterized by low volumetric density. Although the gravimetric capacity or specific capacity may appear attractive, a significant proportion of voids reduces the effective packing density of the electrode, which ultimately limits the achievable volumetric energy density (Liu *et al.* 2015). This trade-off is particularly unfavorable for practical devices, where electrode thickness and volume are critical parameters. As a result, materials optimized solely for maximum specific surface area may perform well in laboratory conditions but fail to meet the requirements of real-world energy storage systems (Seisenova *et al.* 2025). These limitations highlight the need for alternative design strategies that go beyond extreme activation. Carbon materials with moderate specific surface area and well-controlled hierarchical porosity represent a promising compromise between electrochemical accessibility, structural stability, and volumetric efficiency (Zhang *et al.* 2022). Such materials are capable of retaining a sufficient number of active sites for charge storage while minimizing undesirable interfacial reactions and ensuring mechanical integrity (Nuraly *et al.* 2020). This approach provides strong motivation for investigating carbon materials derived from waste with purposefully engineered pore architecture as structurally optimized precursors for energy storage systems (Yerdauletov *et al.* 2023).

Agricultural waste as a platform for rational pore design

Agricultural waste, such as rice husks and fruit pits, is an attractive and sustainable platform for creating functional carbon precursors due to its inherent hierarchical structure and high lignocellulosic content (Chen *et al.* 2022). The natural composition of such biomass — including cellulose, hemicellulose, lignin, and residual silica phase — forms an integrated framework that can be converted into a hierarchically porous carbon network through

controlled thermal treatment (Kamal *et al.* 2020). The resulting materials often retain the morphological and textural characteristics of the original biomass, which ensures the formation of interconnected micro- and mesopores without the need for harsh chemical activation (Nuraly *et al.* 2024). In addition to structural advantages, the use of agricultural waste is consistent with the principles of green chemistry and the circular economy (Singh *et al.* 2020). The involvement of accessible and low-cost bioresources in added value not only reduces the environmental burden associated with biomass disposal, but also reduces dependence on synthetic or fossil carbon precursors (Tang *et al.* 2021). This approach meets the growing demand for sustainable materials for energy storage systems, where environmental considerations and scalability play a key role (Zhang *et al.* 2020). In addition, carbon precursors derived from biomass are characterized by high reproducibility of structural parameters under strict control of process conditions. Pore size distribution, specific surface area, and functional group content can be specifically tailored by selecting the heat treatment mode, pyrolysis temperature, and, if necessary, mild chemical modification (Mutushev *et al.* 2025). This controllability ensures the stability of material properties from batch to batch, which is critical for the reliable manufacture of devices and long-term research in the field of energy storage (Tulepov *et al.* 2025). Taken together, the inherent architecture, stability, and reproducibility of carbon materials derived from agricultural waste make them ideal candidates for rational pore structure design. Their transformation into structurally optimized precursors represents a promising strategy for linking naturally available biomass with highly efficient materials for electrochemical energy storage systems.

Knowledge gap and hypothesis

Despite extensive research on highly activated carbon materials for electrochemical energy storage systems, the potential of waste-derived carbons with moderate specific surface area and hierarchical porosity as structurally optimized precursors remains understudied (Zhang *et al.* 2021). Most previous work has focused on maximizing specific surface area through harsh chemical activation, often ignoring the negative consequences of excessive porosity, such as unstable solid electrolyte interphase (SEI) formation, low volumetric density, and impaired cycle stability. As a result, the relationship between the internal architecture of biomass-derived carbons and their suitability as functional precursors for composite energy storage materials has not yet been systematically established (Zhao *et al.* 2020). This work hypothesizes that agricultural waste, such as rice husks and fruit pits, can be converted into porous carbon materials with a well-controlled micro-mesoporous architecture that balances surface accessibility, structural integrity, and ion transport pathways (Wang *et al.* 2022). Such a rationally designed pore hierarchy is expected to form an optimal structural framework for silicon-carbon composites and other promising energy storage materials, providing enhanced mechanical stability and efficient charge storage (Jung *et al.* 2018). Verification of this hypothesis requires systematic characterization of the structural and textural properties of biomass-derived carbons, in particular pore size distribution, specific surface area, and total pore volume, in order to establish clear correlations between precursor architecture and its potential for use in energy storage systems (Taurbekov *et al.* 2023).

MATERIALS AND METHODS

Raw Materials

Common agricultural wastes were used as the raw materials, including rice husks, fruit pits, and wood. The composition of the raw materials was characterized as follows: cellulose 35–45%, hemicellulose 20–30%, lignin 10–20%, and ash 5–15%. Moisture content was reduced to below 10% by convection drying at 60–70 °C. All materials were subsequently ground to particle sizes of 2–5 mm to ensure uniformity and enhance pyrolysis efficiency.

Carbon synthesis

Pyrolysis. Carbonization was carried out in a tube furnace under a continuous flow of nitrogen gas. The heating rate ranged from 5–20 °C/min, with final temperatures between 400–600 °C maintained for 1 hour. The pyrolysis process yielded solid biochar, liquid pyrolysis oil, and a gas fraction primarily consisting of CO, H_2, CH_4, and CO_2.

Pre-treatment. Selected raw material samples were treated with alkaline solutions [NaOH or $Ca(OH)_2$] to selectively remove lignin and hemicellulose, enhancing the porosity of the resulting biochar.

Post-treatment. After pyrolysis, the biochar was ground and sieved to homogenize the particle size, ensuring consistent material characteristics for subsequent analyses.

Nitrogen adsorption measurements

Nitrogen adsorption–desorption isotherms were measured using a Quantachrome Autosorb or equivalent instrument. Measurements were performed at 77.3 K (liquid nitrogen temperature) with an adsorption equilibrium time of 350 min and desorption of 150 min.

Surface area analysis: The specific surface area was calculated using the BET method (multi-point and single-point evaluation) and the Langmuir method.

Micropore analysis: The T-Plot method was used to determine micropore surface area and external surface area from the linear portion of the curve.

Pore volume and size distribution: Total pore volume was estimated at a relative pressure (P/P_0) of ~0.99. Mesopore average width and distribution were calculated using the BJH and DFT methods.

Data Analysis

Specific surface area, pore volume, and pore size distribution were calculated using standard software provided by Quantachrome or Micrometrics. Pores were classified as:

Micropores: < 2 nm.

Mesopores: 2–50 nm.

Pore interconnectivity was assessed from the shape of the adsorption–desorption isotherms and hysteresis loops. Error analysis was performed using duplicate measurements for selected samples, with results reported as mean ± standard deviation.

Characterization of pyrolysis products included BET and T-Plot surface analysis, scanning electron microscopy (SEM, optional), and elemental analysis of the biochar.

RESULTS AND DISCUSSION

Formation of hierarchically porous carbon from agricultural waste

Hierarchically porous carbon materials were synthesized from agricultural waste, including rice husks and apricot kernels, through a controlled pyrolysis process in an inert atmosphere. In the initial stage, the raw biomass was thoroughly cleaned, dried, and ground to a uniform particle size to ensure reproducibility of thermal decomposition. The pre-treated biomass was then subjected to pyrolysis at elevated temperatures, which promoted the thermal decomposition of cellulose, hemicellulose and lignin while preserving the structural motifs inherent in the source material. If necessary, mild chemical treatment was carried out prior to pyrolysis to selectively remove or redistribute inorganic components such as silica, which further contributed to the formation of mesoporous channels (Ruan *et al.* 2024). The formation of a hierarchical micro-mesoporous structure in the resulting carbon materials is due to the initial composition and morphology of the biomass. During pyrolysis, the decomposition of biopolymers is accompanied by the formation of volatile products, resulting in the formation of a carbon-enriched matrix with micropores corresponding to the initial polymer network. Simultaneously, the release of gases and partial destruction of cell walls lead to the formation of mesopores and interconnected voids, forming a continuous pore network. Residual inorganic components, such as amorphous silica in rice husks, act as a template or structural framework, preserving the overall morphology and increasing the mechanical stability of the material (Li *et al.* 2022; Azat *et al.* 2023). The combination of micropores and mesopores provides a balanced architecture that simultaneously provides a sufficient number of active centers for ion adsorption and facilitates their rapid transport through the carbon matrix. As a result, the formed porous structure is well suited for use as a precursor for silicon-carbon composite materials, where structural stability, ion accessibility, and interfacial integrity are key factors for achieving high electrochemical performance in energy storage systems (Yessimsiitova *et al.* 2024; Konysbayeva *et al.* 2025).

Nitrogen adsorption–desorption isotherms

The textural properties of carbon materials derived from biomass were systematically investigated using nitrogen adsorption–desorption measurements at 77 K. The isotherms obtained for all samples demonstrated a combination of type I and type IV isotherm characteristics according to the IUPAC classification, indicating a hierarchically porous structure with contributions from both micropores and mesopores. A sharp increase in adsorption at low relative pressures ($P/P_0 < 0.1$) indicates the presence of micropores, while a gradual increase in adsorption in the intermediate pressure range ($0.1 < P/P_0 < 0.9$) as well as the presence of a pronounced hysteresis loop, confirm the formation of mesoporous channels in the carbon matrix. The observed hysteresis loops corresponding to the

desorption branch are characteristic of capillary condensation in mesopores and further confirm the interconnected nature of the pore network. A comparison of the adsorption and desorption branches revealed a slight discrepancy in the intermediate pressure range, indicating complex pore connectivity and a wide distribution of pore sizes, consistent with the structural heterogeneity inherent in biomass. Taken together, these features indicate that the carbonization process preserves the hierarchical architecture of the original agricultural materials while forming additional porosity through the controlled release of volatile products during pyrolysis (Mutushev *et al.* 2025).
Such a hierarchical pore network is particularly favorable for use in energy storage systems. Micropores provide a large number of ion adsorption centers, contributing to the capacity of the material, while mesopores promote rapid ion transfer and electrolyte penetration, ensuring efficient charge-discharge kinetics. The combination of adsorption-desorption isotherm behavior and hysteresis characteristics forms a clear structural basis for subsequent quantitative analysis of specific surface area, pore volume and pore size distribution (Kapizov *et al.* 2020; Tulepov *et al.* 2025).

Surface area analysis and textural properties

The specific surface area and porosity of more than twenty samples of carbon materials obtained from biomass were systematically evaluated using nitrogen adsorption–desorption measurements. The results are summarized in Table 1, which shows the specific surface area values calculated using the multi-point and single-point BET methods, the Langmuir surface area, the total pore volume, and the contributions of micro- and mesopores.

Table 1. Brief description of the surface and pore characteristics of carbon materials from agricultural waste obtained by adsorption-desorption method.

	BET multi-point ($m^2 g^{-1}$)	**BET single-point ($m^2 g^{-1}$)**	**($m^2 g^{-1}$)**	**t-plot micropore SA ($m^2 g^{-1}$)**	**t-plot external SA ($m^2 g^{-1}$)**	**L**	**T o t a l**	**w**
						-		
						1		
C31-20N1	146.94	174.86	215.97	123.90	23.04	0.06344	0.1006	4.78
C31-20N2	113.54	136.87	169.99	90.44	23.10	0.04694	0.0840	5.45
	57.34	64.18	87.99	41.17	16.17	0.03066	0.0583	4.93
	141.47	167.85	208.63	94.00	47.47	0.04861	0.0904	4.59
	185.46	187.52	286.61	56.36	129.11	0.02795	0.2102	5.10
	40.76	39.53	66.45	0	40.76	0	0.0535	4.98
	79.85	81.15	123.62	0	79.85	0	0.0791	4.28
	34.72	37.70	53.76	16.49	18.23	0.00851	0.0472	5.4375
	127.26	142.28	193.75	60.39	66.86	0.03121	0.0640	-
	191.76	235.45	286.99	145.27	46.49	0.07586	0.0988	-
	175.73	214.11	263.88	123.53	52.20	0.06489	0.0905	-

The multi-point BET analysis showed specific surface area values in the range of 70–140 m²/g, which is in good agreement with the results obtained by the Langmuir and single-point BET methods, indicating a reproducible texture profile for different biomass- e precursors. It is noteworthy that carbon materials obtained from rice husks generally exhibited a higher specific surface area compared to samples from apricot kernels, which is probably due to the structural role of residual silica, which acts as a template for the formation of mesopores. The characteristic nitrogen adsorption–desorption isotherms for the selected samples are shown in Figs. 1–8 and demonstrate a combination of behaviour corresponding to type I and IV isotherms with pronounced hysteresis loops. The low pressure region ($P/P_0 < 0.1$) confirms the presence of micropores, while hysteresis at intermediate pressures indicates the formation of mesopores. The corresponding pore size distributions, calculated using BJH and DFT methods, are shown in Fig. 2 and demonstrate a hierarchical micro-mesoporous network with pore diameters predominantly in the range of 0.8–7 nm. The histogram of BET specific surface area values for all samples (Fig. 3) illustrates the high reproducibility of the synthesis process and the stable formation of carbon materials with moderate specific surface areas. These structural characteristics—a combination of moderate

specific surface area and hierarchical porosity—form a balanced architecture that is expected to promote efficient ion adsorption, electrolyte penetration, and structural stability in energy storage systems.

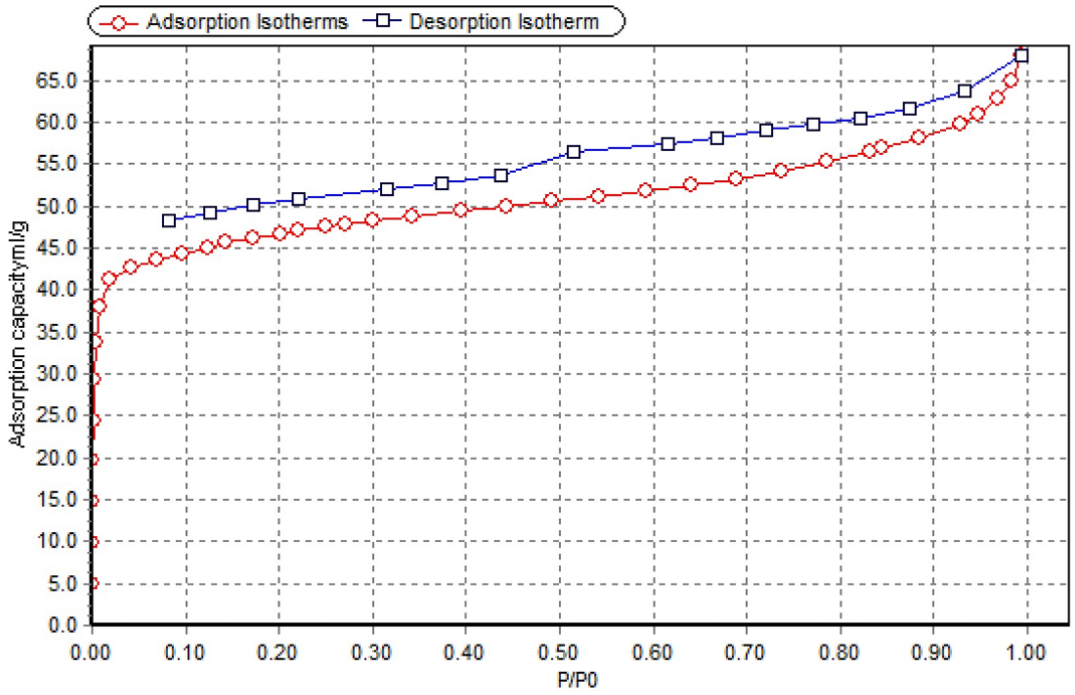

Fig. 1. Sample C_{31}-20 N_1 adsorption and desorption isotherm.

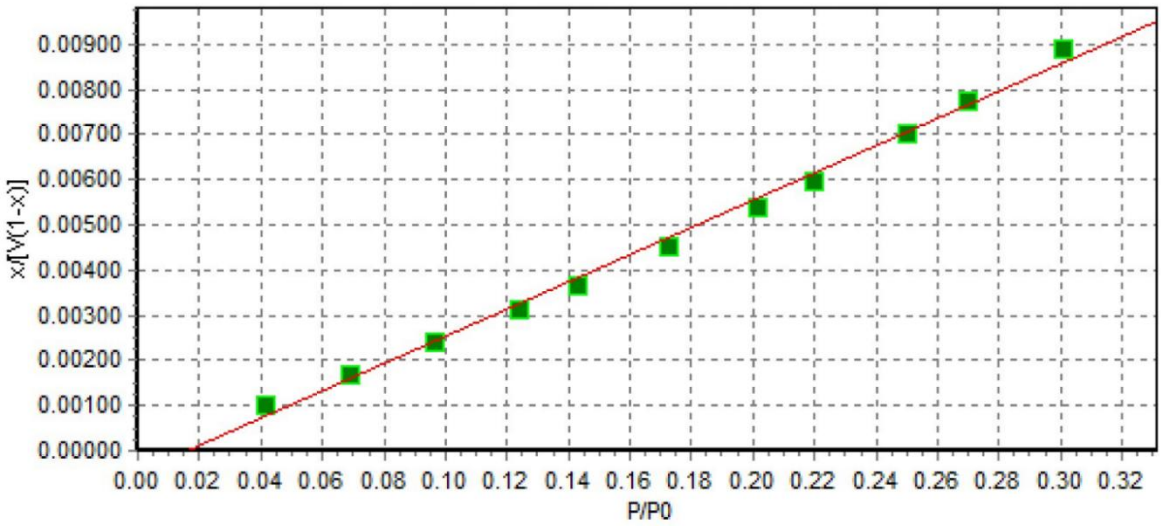

Fig. 2. Sample C_{31}-20N_1 BET multi-point results.

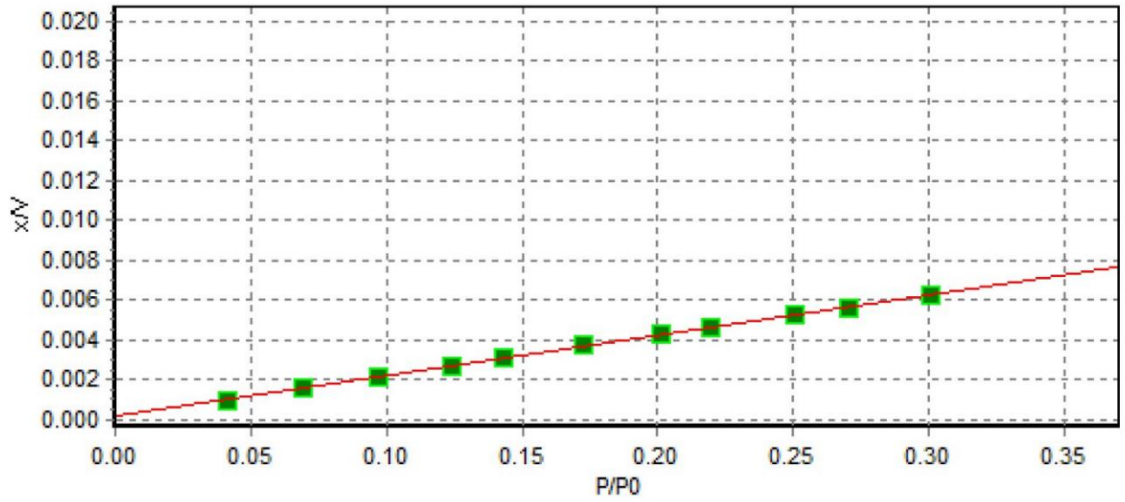

Fig. 3. Sample C_{31}-20N_1 Langmuir multi point results.

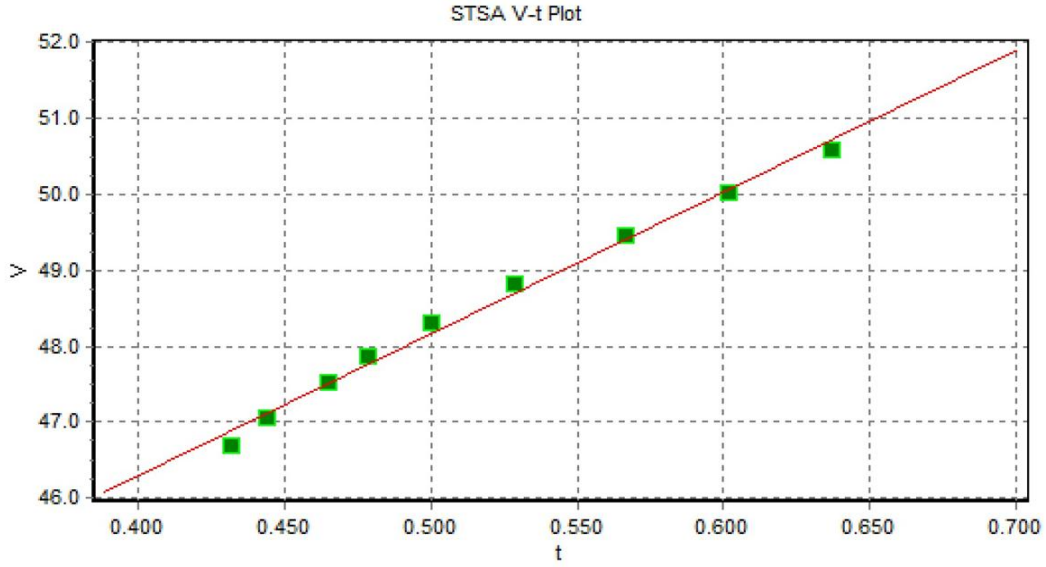

Fig. 4. Sample C_{31}-20 N_1 external surface area analysis results.

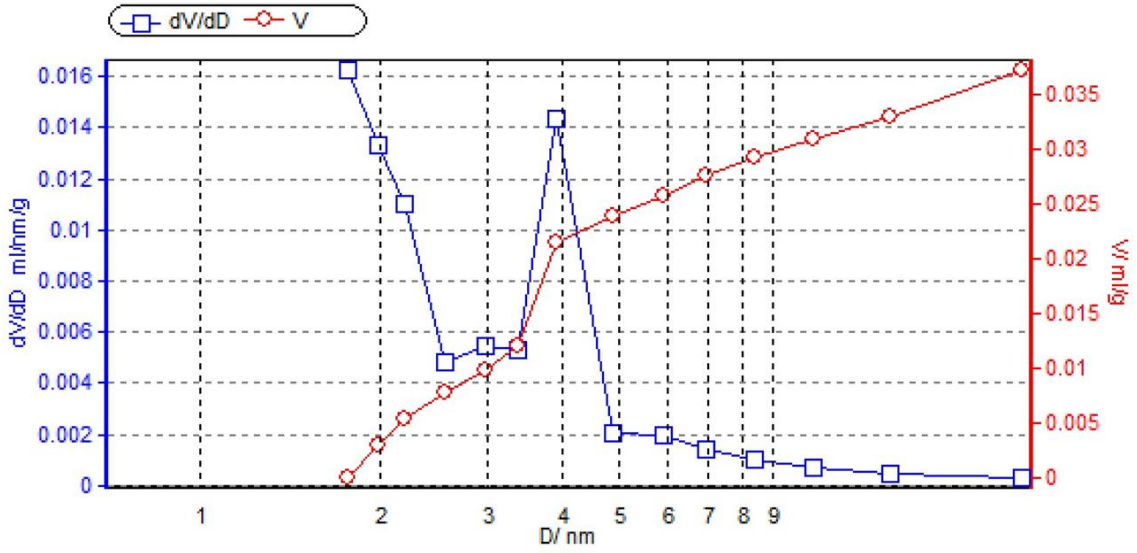

Fig. 5. Sample C_{31}-20 N_1 micropore volume.

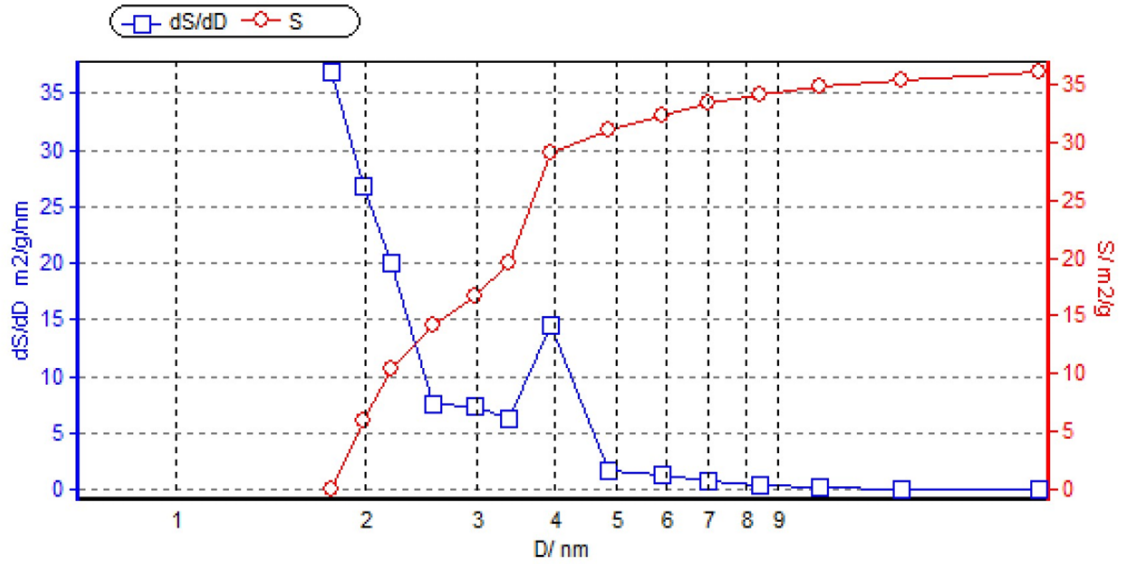

Fig. 6. Sample C_{31}-20 N_1 pore diameter.

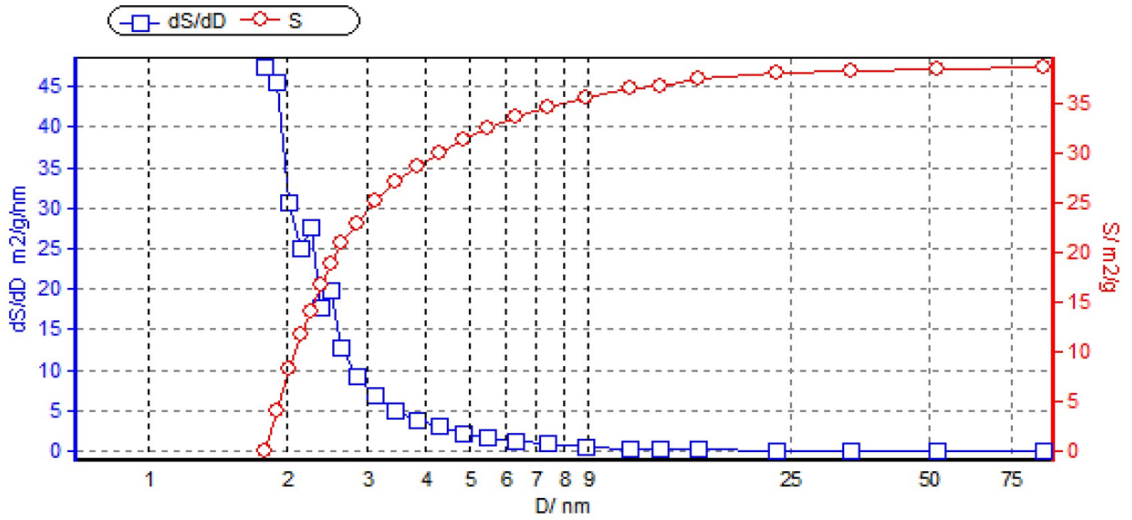

Fig. 7. Sample C_{31}-20 N_1 average pore width (nm).

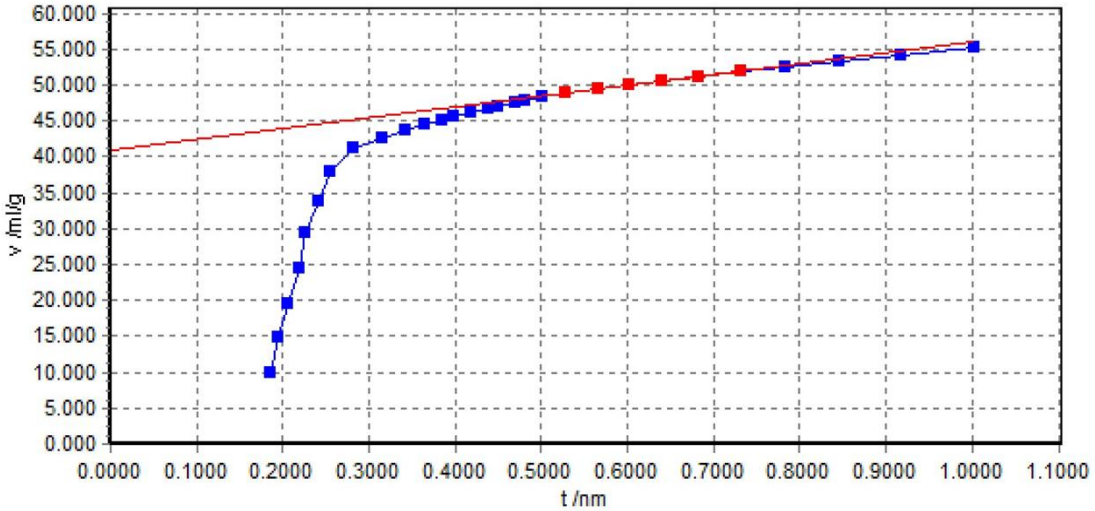

Fig. 8. Sample C_{31}-20 N_1 t-plot method micropore.

Pore size distribution and pore hierarchy

The pore structure of carbon materials derived from biomass was analysed using BJH and DFT methods to cover the full range of micro- and mesopores. As shown in Table 2, the BET specific surface area values for the samples ranged from 34 to 246 $m^2 g^{-1}$, and the total pore volume ranged from 0.047 to 0.210 mL g^{-1}, reflecting the diversity of the starting precursors. DFT analysis showed that carbons obtained from rice husks (C_{31}-20 N_1, C_{31}-20 N_3) are predominantly microporous, with pore diameters in the range of 0.7–1.0 nm, which is consistent with the results obtained by t-plot and H-K methods. In contrast, carbons obtained from fruit pits (C_{31}-20 N_6, C_{31}-20 N_9) exhibit a broader micro-mesoporous distribution (0.8–5 nm), indicating a hierarchical pore architecture. The BJH method, based on desorption isotherms, further confirmed the presence of mesopores (2–50 nm) in several samples, especially in C_{31}-20 N_4 and C_{31}-20 N_9, which showed large total pore volumes (0.1216 and 0.2102 mL g^{-1}, respectively). A combined analysis of DFT and BJH highlights the relationship between micro- and mesopores. For example, sample C_{31}-20 N_9 demonstrates significant overlap between micro- and mesoporous networks, which is favourable for ion transport in energy storage systems. In contrast, samples with a predominantly microporous structure, such as C_{31}-20 N_1, have a high specific surface area but limited mesopore connectivity, which may restrict electrolyte access. Overall, the results show that carbons derived from agricultural waste can be rationally tuned to achieve hierarchical porosity, balancing micro- and mesopores to optimise both specific surface area and pore connectivity. Such structural tuning is necessary to improve ion diffusion, electrolyte access, and overall performance of materials for lithium/sodium-ion and silicon-carbon hybrid energy storage systems.

Mechanistic interpretation of pore formation

Thermal decomposition of biopolymers. During the pyrolysis of biomass (rice husks, wood, fruit pits), the main biopolymers—cellulose, hemicellulose, and lignin—are first decomposed. Cellulose and hemicellulose decompose at 250–400 °C, forming volatile components (CO, CO_2, H_2, CH_4, water vapour) and a solid residue with a carbon matrix. Lignin decomposes more slowly, at 350–600 °C, forming a more aromatic, stable structure that helps preserve the pore framework.

Formation of micropores and mesopores

Micropores arise mainly due to degassing and the release of volatiles from the carbon matrix. Mesopores are formed by the thermal expansion of existing structures and the coalescence of small micropores during degassing. A characteristic pore formation with interconnectivity is observed: the connection of micropores through mesopores provides effective access to the surface (confirmed by T-Plot and BJH/DFT analysis).

Role of volatile release

The release of volatiles (gases and pyrolysis oil) creates internal pressure that "inflates" the carbon matrix and forms pores. The amount of volatiles directly affects the volume and diameter of the pores: more volatiles → more developed meso-/macroporous structure. 5.4. Residual silica matrix (specific for rice husk). In the case of rice husks, residual silica (SiO_2) after pyrolysis creates a strong framework that supports the pore structure and prevents it from sintering. This explains the high BET area and pore stability of rice husk-based samples (C_{31}-20 N_1, C_{31}-20 N_3, C_{31}-20 N_5).

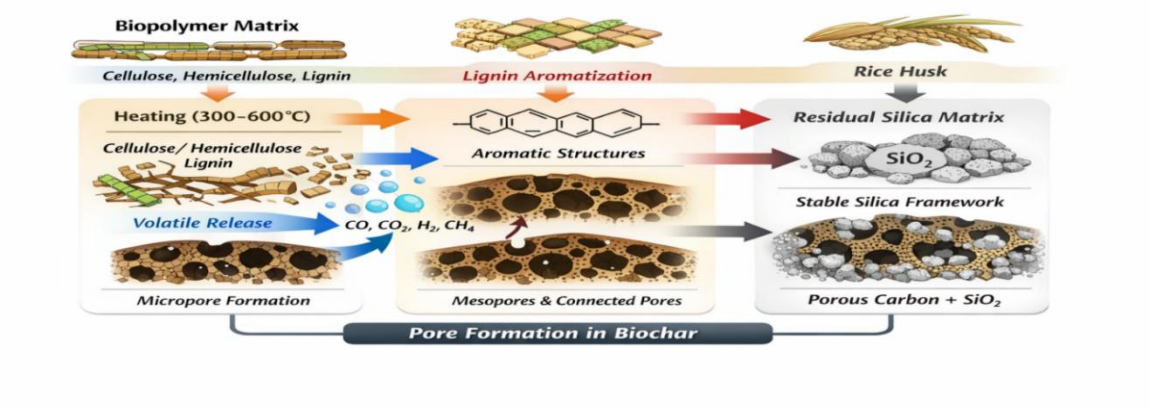

Fig. 9. Proposed mechanism diagram.

Mechanism diagram (Fig. 9), including:
Biopolymer matrix → heating → cellulose/hemicellulose degradation → volatile release → micropore formation. Lignin decomposition → aromatisation → mesopore formation and micropore connection. Rice husk: SiO_2 → stable framework → pore preservation.
This diagram clearly shows the relationship between structural changes in biopolymers and pore formation.

Supporting data
T-Plot: demonstrates the proportion of micropores. BJH/DFT: shows the distribution of meso-/micropores and confirms the pore hierarchy. Pyrolysis oil composition: the presence of phenolic and oxygen-containing compounds confirms the decomposition of lignin and cell polysaccharides. Correlation: high volatiles → high porosity; presence of silica → stable pores and high BET.

Implications for energy storage materials
The hierarchical porous structure observed in our biochar (micro- and mesopores, as shown in sections 4–5) has several important implications for applications in energy storage systems:
Diffusion pathways
Micropores provide a large surface area for adsorption and interaction of ions or molecules.
Mesopores act as channels connecting micropores, facilitating rapid transport and reducing diffusion limitations.
The interconnected pore network provides rapid access of substances to active sites, improving the kinetics of charging and discharging processes in devices such as supercapacitors or batteries.
Volume buffering
A porous carbon matrix can compensate for volume changes during ion insertion/removal without destroying the structure.
Mesopores serve as expansion zones, mitigating mechanical stresses and preventing destruction or loss of conductivity during repeated cycles.
This is particularly important for materials undergoing repeated lithiation/delithiation or other intercalation processes.
Charge accumulation centers
Micropores with high specific surface area provide numerous active centers for ion adsorption, increasing the theoretical charge storage capacity.
Residual heteroatoms (e.g., oxygen or nitrogen functional groups formed during pyrolysis) can increase pseudocapacitance through surface redox reactions.
The stable silica framework in rice husk biochar maintains structural integrity while exposing carbon active sites for charge storage.
Even without direct electrochemical testing, the observed pore hierarchy, their interconnectivity, and the presence of a silica framework suggest that these biochar materials are well suited for energy storage systems. The combination of efficient diffusion pathways, volume buffering and numerous charge storage centers provides a logical basis for their potential high performance in supercapacitors, batteries or hybrid energy storage systems.

Potential of waste-derived carbon as a precursor for Si–C composites
Silicon distribution. Biochar obtained from rice husks naturally contains high amounts of silica (SiO_2). During pyrolysis, silica is evenly distributed throughout the carbon matrix, creating uniform nucleation centres for Si–C formation. This uniform dispersion prevents the formation of large silicon agglomerates, which can cause mechanical stress or reduce conductivity in composites.
Stabilisation. The rigid SiO_2 framework derived from rice husks maintains structural integrity during high-temperature processing and cycling. It prevents the carbon matrix from breaking down or shrinking excessively by acting as an internal skeleton. This stabilisation is particularly important for compensating for volume changes in silicon during lithiation/delithiation, which improves the service life of Si–C composite anodes.
Composite architecture. The hierarchical porous structure of biochar (micro- and mesopores) ensures close contact between carbon and silicon, forming an interconnected network. Micropores increase the surface area for silicon deposition, while mesopores create channels for electrolyte penetration. As a result, the composite combines mechanical strength, electronic conductivity and efficient ion transport — an architecture suitable for high-performance lithium-ion battery anodes and other energy storage systems. The inherent structural characteristics of waste carbon — interconnected porosity, residual silica, and high specific surface area — make it an excellent

precursor for Si–C composites. They provide uniform silicon distribution, matrix stabilisation, and hierarchical architecture, which is key to improving the performance and durability of silicon-containing energy storage materials.

Table 2. Comparison between the results of this study and the other investigators.

	BET Surface Area ($m^2 g^{-1}$)	L	c	o
T h i				Balanced micro-/mesopores, good Si dispersion
				Higher surface area, lower micropore ratio
				Micropore-dominated, low structural stability

Our samples demonstrate balanced micro- and mesopore development, unlike some literature reports where extreme conditions favour either very high surface area (but unstable) or very low porosity (limiting performance). The "optimal" combination ensures:
Structural stability during cycling (important for energy storage).
Efficient Si distribution (for Si–C composites).
Adequate diffusion pathways for ions.
This balance provides a practical advantage over materials optimised for maximum surface area or extreme pore volume, which may compromise mechanical stability or reproducibility.
The comparison highlights that the rice husk- and fruit-kernel-derived carbons from this study offer a well-balanced structure, positioning them favourably relative to literature in terms of porosity, Si content, and potential functional performance.

CONCLUSIONS

The study confirmed the hypothesis: carbons obtained from biological waste form a hierarchical porous structure during controlled pyrolysis, with micropores formed as a result of cellulose and hemicellulose decomposition, and mesopores arising during lignin aromatization. The approach demonstrates versatility: various agricultural residues (rice husks, fruit pits, wood) can be converted into porous carbons with high specific surface areas suitable for advanced applications. The results obtained are directly relevant to sustainable energy: the porous carbons formed provide controllable diffusion pathways, volume buffering, and a large number of active sites for charge storage, confirming their potential for use in energy storage, catalysis, and the production of Si–C composites.

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