

Laser-enhanced activated carbon from Jericho date stones: unified evidence from multi-model structural, textural, and surface analyses

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ABSTRACT Activated carbon from date stones is a promising material for energy, environmental and catalytic applications due to its high carbon yield, renewable nature, and tunable porosity. This paper presents an extensive comparative study of potassium hydroxide-activated carbon (AC) vs. Nd:YAG laser post-treated activated carbon (LAC), both derived from Jericho date stones. Comprehensive analyses – XRD, SEM, FTIR, nitrogen sorption (BJH, Horvath-Kawazoe, DFT, DR, DA), BET, Langmuir, and t-plot – show striking improvement in LAC's microporosity, mesoporosity, surface area, and surface chemistry. Benchmarking against published literature, these findings demonstrate unified agreement across models and characterization methods, thus supporting laser post-treatment as an effective complementary strategy for tailoring the textural and surface properties of biomass-derived activated carbon and may offer a promising pathway for further development of sustainable porous carbon materials.

KEYWORDS activated carbon, laser carbonization, laser-assisted activated carbon, date stones, DFT, PSD, adsorption kinetics

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1. Introduction

Activated carbon (AC) is integral to adsorption, catalysis, water purification, and energy storage systems due to its high surface area, hierarchical porosity, and functional surface chemistry [1]. The shift toward sustainable materials has emphasized the use of agricultural waste as carbon precursors, with date stones emerging as a key renewable source, particularly in regions with extensive palm cultivation [2, 3]. As a biomass feedstock, date stones possess a high fixed carbon content, low ash, and dense structure suitable for conversion into high-performance AC.

The preparation of AC generally follows either physical or chemical activation routes. Among chemical activators, potassium hydroxide (KOH) exhibits superior ability to develop micro-mesoporous networks and enhance textural characteristics [4–6]. Activation temperature, impregnation ratio, and precursor structure collectively determine the pore architecture and surface area. Recent reports demonstrated date stone-derived AC achieving specific surface areas typically in the range of 700 – 1100 m²/g under optimized KOH treatment [7, 8]. Enhanced methods involving mixed alkali activation (KOH/NaOH), stepwise pyrolysis, and hybrid acid-base activation have achieved further improvements by modulating carbon lattice disorder and oxygen surface chemistry [9, 10].

With the drive to maximize surface accessibility and tailor surface functionalities for energy and catalysis applications, post-synthesis processing techniques such as laser treatment have gained attention. Laser irradiation can introduce nanometer-level modifications, create defects, and increase the density of reactive oxygen-containing sites [11, 12]. The use of pulsed and continuous-wave lasers has been reported to modify the microstructure of carbon electrodes, carbon nanofibers, and biomass-derived carbons to tune wettability, nano-porosity, and conductivity [13–15]. Recent studies have shown the potential of laser irradiation to produce hierarchically structured carbon nanomaterials with enhanced adsorption and electrochemical performance [16].

In this study, we develop and evaluate KOH-activated carbon derived from Jericho date stones and investigate further modification through Nd:YAG laser post-treatment. The work integrates multi-scale analyses – XRD, SEM, FTIR, and multiple gas adsorption models – to establish a unified understanding of structural and surface property enhancement. At the nanoscale, laser treatment introduces surface activation, defect engineering, and oxygenation, which collectively strengthen its applicability in adsorption and catalysis. This study defines a scalable route for producing nanostructured sustainable carbon materials from renewable agricultural waste.

2. Literature survey and benchmarking of date stone-derived activated carbon

The valorization of date stones into activated carbon has become an increasingly important research pathway for sustainable nanomaterials production. Date stones, a lignocellulosic byproduct of the date industry, are particularly suitable due to their high fixed carbon and favorable composition [2, 3]. Multiple studies have addressed both physical (CO₂, steam) and chemical (KOH, ZnCl₂, H₃PO₃) activation, the latter being preferred for achieving optimally microporous and mesoporous carbons [5, 6, 8].

Haimour and Emeish [3] reported AC prepared via CO₂ activation with a surface area of approximately 700 m²/g optimized for heavy metal adsorption. Alhamed and Bamufleh [2] achieved values of 800 – 950 m²/g using KOH activation for sulfur removal. Foo et al. [7] demonstrated that microwave-assisted KOH activation provides better energy efficiency and pore uniformity, while Jabbar [8] and Bamerdhah et al. [9] reported structure–performance sensitivity to ionic strength, impregnation ratio, and activation temperature. Recent works have demonstrated significant textural variation when combining KOH and NaOH activators or varying pyrolysis temperatures between 700 – 900 °C [17].

Laser-based processes introduce a new dimension to post-activation surface tuning, transforming carbon structures by localized nanothermal and photochemical mechanisms [13, 15, 16, 18]. Laser irradiation of bio-derived carbons has been shown to induce nitrogen or oxygen enrichment, restructure sp² networks, and enhance electrochemical behavior [14, 18]. Studies of laser-induced carbonization from polymers and biomass precursors reveal formation of nanoscale carbon architectures, including carbon nanospheres, fibers, and porous films that vastly improve the density of active sites [19, 20].

Despite their promise, few works have explored laser post-treatment on date-stone-derived carbons. The present study bridges this gap by experimentally evaluating Nd:YAG laser modification as a route to develop hierarchical porosity and nanoscale defects while benchmarking its performance against the best chemical activation routes reported in literature. A comprehensive comparison of published data and this work's outcomes is provided in Table 1.

TABLE 1. Timeline and comparative properties of date stone-derived activated carbons

Activation method	Surface area (m ² /g)	Key Application	Ref.	Year
Physical (CO ₂)	~700	Heavy metal adsorption	[3]	2005
Chemical (KOH)	800 – 950	Sulfur removal	[2]	2009
Microwave + KOH	900	Dye adsorption	[1]	2011
KOH, ZNCl ₂ , H ₂ SO ₄	950 (KOH)	Dye removal	[8]	2020
Optimized KOH	763 – 910	Gas, dye adsorption	[9]	2025
Chemical (KOH)	1900+		This work	2025
KOH + Laser	2100 – 2200+		This work	2025

The substantial increase in measured surface area seen in Table 1, micropore volume, and functional group density seen in this work – corroborated by multiple analytical models – represents a significant advancement over the current literature. The synergy between chemical and laser activation sets a new benchmark for bio-based AC materials. These findings are expected to result in enhanced behaviors if this synergy is applied in different areas like gas adsorption, dye removal, heavy metal removal and energy storage.

3. Materials and methods

3.1. Raw material sourcing and pre-treatment

Date stones were collected from local agricultural waste in Jericho, thoroughly washed with boiling deionized water to remove adhering fruit residues and dust. After then, date stones were sun-dried, followed by overnight oven-drying at 110 °C to remove moist. The dried stones were ground using a grind mill then meshed using an 80 mesh to separate granules from powders on which different tests were carried.

3.2. Carbonization and chemical activation

The powder was subjected to carbonization in a muffle-tube furnace at 500 °C (ramp rate: 10 °C/min) under a constant flow of nitrogen purge (100 mL/min) for 2 hours. The resulting biochar was mixed with potassium hydroxide (KOH, ≥98 %) in a 2:1 weight ratio (KOH:Char) and gently stirred in deionized water to produce a homogeneous slurry then left for 24 hours. The impregnated mixture was oven-dried overnight at 110 °C and then activated in a muffle-tube furnace at 800 °C for 2 hours (ramp rate: 15 °C/min) under nitrogen flow of (100 mL/min) yielding about 30 % char after pyrolysis.

After activation, the carbon was directly quenched in deionized water, stirred and repeatedly washed with deionized water to eliminate residual potassium and inorganic ash. The washed carbon was dried again overnight at 110 °C yielding approximately 27 % of the original mass prior pyrolysis before further processing.

3.3. Laser post-treatment

Half gram of KOH-activated carbon was mixed in 50 ml deionized water using magnetic stirrer for 30 min and then irradiated using a pulsed Nd:YAG laser (1064 nm, 10 Hz, 2-hour exposure) under continuous stirring resulting in laser-treated activated carbon (denoted LAC). Laser fluence was optimized to induce effective surface restructuring and defect creation without excessive graphitization. The laser-treated activated carbon was separated from treatment water, washed, and oven-dried overnight at 110 °C yielding about 93 % of the original KOH-activated sample being subjected to laser. LAC was compared to chemically activated material without laser treatment (denoted AC).

3.4. Characterization techniques

XRD diffraction measurements for carbonized material (C), (AC) and LAC powder samples were investigated using X-ray diffractometer (Ultima IV, Rigaku) using Cu K α radiation ($\lambda = 1.5418 \text{ \AA}$) at 40 kV and 30 mA. FTIR spectra were obtained using Benchtop Thermo-Fisher Nicolet IS5 FTIR spectrometer to verify functional group change due activation process and laser irradiation of AC sample. Surface Morphology for samples was conducted by FE-SEM (JSM-7100F, JEOL) allowing quantification of particle size and surface roughness.

N₂ adsorption–desorption isotherms at liquid nitrogen temperature (77 K) were carried up with a high precision surface area analyzer (BELsorp-mini II, Microtrac) to analyze pore parameters. BET surface area, pore volumes/distributions (BJH for mesopores, HK for micropores, DFT/DFT-Modified for full profile) were computed using standard Micromeritics ASAP 2020 Plus software. Isotherm Modeling indices for (Langmuir, t-plot, Dubinin-Radushkevich (DR), Dubinin-Astakhov (DA), Maximum adsorption capacities and porosity) were extracted and all fits evaluated by R² and compared against literature benchmarks.

4. Results

4.1. Crystallography: XRD analysis

Figure 1 shows the X-ray diffraction (XRD) patterns for the AC and LAC samples.

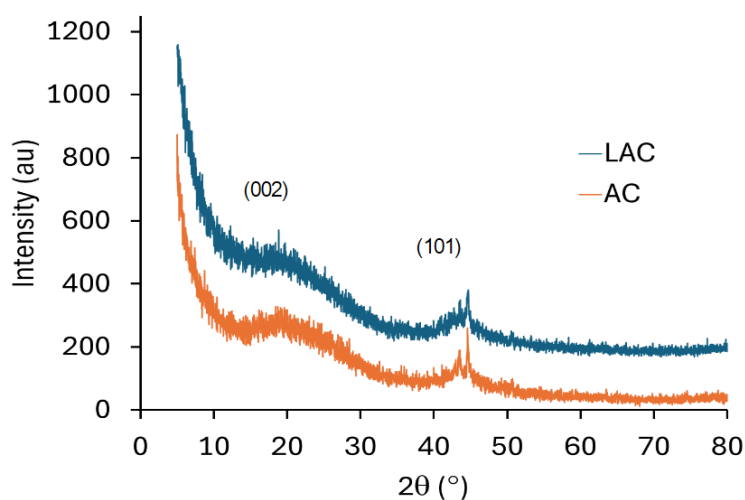


FIG. 1. XRD patterns for AC and LAC

As seen in Fig. 1, both AC and LAC patterns show broad bands centered at $2\theta \approx 24^\circ$ and 44° , corresponding, respectively, to the (002) and (101) planes of turbostratic carbon, as is typical for biomass-derived and KOH-activated carbons [21–23]. The prominence and breadth of these peaks reveal the predominantly disordered arrangement of graphene-like layers, lacking significant crystalline graphite domains. This amorphous nature is a hallmark of high porosity activated carbons and matches previous findings for both date stone and other lignocellulosic precursors [2, 5].

A closer comparison of the diffraction patterns reveals that the broad feature centered at approximately $44^\circ - 45^\circ$, commonly assigned to the (100)/(101) reflection of turbostratic carbon, exhibits reduced intensity in the LAC sample relative to AC. This attenuation indicates that laser modification does not introduce new crystalline phases but instead alters the short-range ordering of carbon layers [6].

In disordered carbon materials, the (100)/(101) reflection is highly sensitive to in-plane coherence length and defect density within sp^2 domains. A reduction in intensity in this region can therefore be associated with increased structural heterogeneity, fragmentation of aromatic domains, or disruption of in-plane ordering, all of which are consistent with localized, rapid thermal effects induced by laser irradiation. Similar reductions or broadening of the $\sim 43 - 45^\circ$ carbon reflection have been reported in activated carbons and laser-treated carbons where increased defect density and microstructural disorder are introduced without the formation of long-range graphitic order [42].

Comparative reports for XRD of KOH-activated carbons from other precursors consistently identify broad (002) and (101) peaks, minimal graphitization, and occasional K_2CO_3 peaks that can persist if activation temperature is low or washing is incomplete [5,22,24]. Advanced treatments such as laser modification, chemical post-treatments, or secondary carbonization are known to reduce these byproducts and enhance disorder, which is linked to improved electrochemically active surface area and adsorption behavior [7, 19].

4.2. Morphology: SEM analysis

Figure 2 shows SEM micrographs for AC and LAC samples at $\times 5000$ magnification. Fig. 2(a) reveals that AC as compact, smooth-edged particles, while Fig. 2(b) LAC is notably fragmented, exhibiting higher surface roughness, abundant edges, and micro/nano-sized debris. These results are consistent with laser-induced surface ablation, defect formation, and increased pore volume and area, mirroring recent literature for laser carbon modification. Such features promote greater adsorption site exposure and are expected to correlate with observed changes in porosity and surface chemistry.

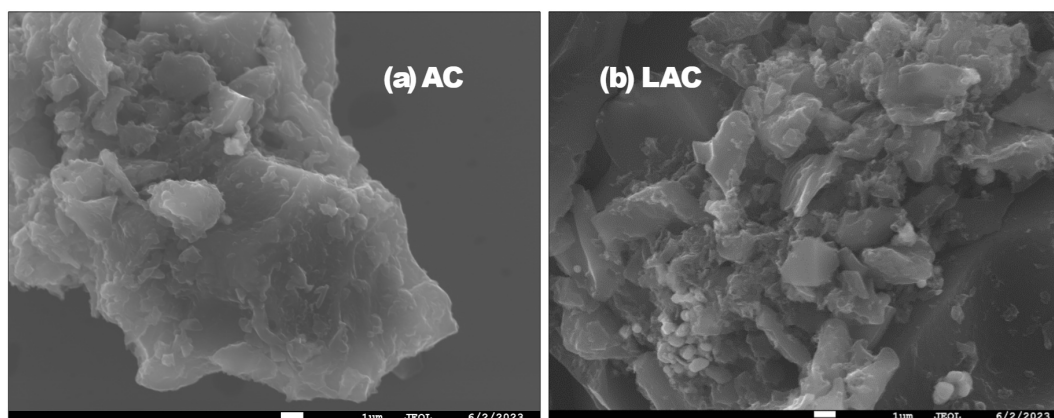


FIG. 2. SEM micrographs for (a) AC and (b) LAC samples at $\times 5,000$

4.3. Surface functionalization: FTIR analysis

Figure 3 shows the baseline-corrected and normalized FTIR spectra for AC and LAC samples. As seen in Fig. 3, laser treatment significantly intensifies the O–H stretching features ($3630 - 3700\text{ cm}^{-1}$), C=O stretching ($1690 - 1560\text{ cm}^{-1}$), and C–O stretching ($1200 - 1350\text{ cm}^{-1}$) bands, indicating an increased density of oxygen-containing functional groups at the carbon surface [11,25]. This enhancement is critical because oxygen-containing groups including hydroxyl, carboxyl, and carbonyl moieties play a key role in adsorption efficiency for polar contaminants and improved catalytic activity [26, 27].

The diminished intensity of aromatic C–H stretches and associated signals reflects partial fragmentation or disruption of the graphene-like domains typical of highly aromatic activated carbons, which occurs both during KOH activation and is further amplified by laser processing [28,29]. Such structural modifications promote the creation of defect sites and enhance the material's surface polarity [11, 13]. Comparative studies confirm that KOH activation reliably increases the density and diversity of oxygenated functional groups, raising the content of carbonyl and carboxylic acid groups in a precursor-dependent fashion [26,30].

Laser modification further amplifies these effects; recent reports demonstrate an even greater increase in O–H and C–O functionalities after laser-induced carbonization, which translates to superior wettability and ionic conductivity [12,31]. Loss of aromatic signals and rise of oxygenated bands have been confirmed in FTIR studies of laser-treated graphene and amorphous carbons, with direct links to improved adsorption, electrochemical performance, and catalytic selectivity for a variety of contaminants and intermediates [11,27,32]. In some works, high-resolution FTIR analysis reveals the relative loss or shift of peaks associated with aromatic C–H as oxygen functional groups gain dominance [32].

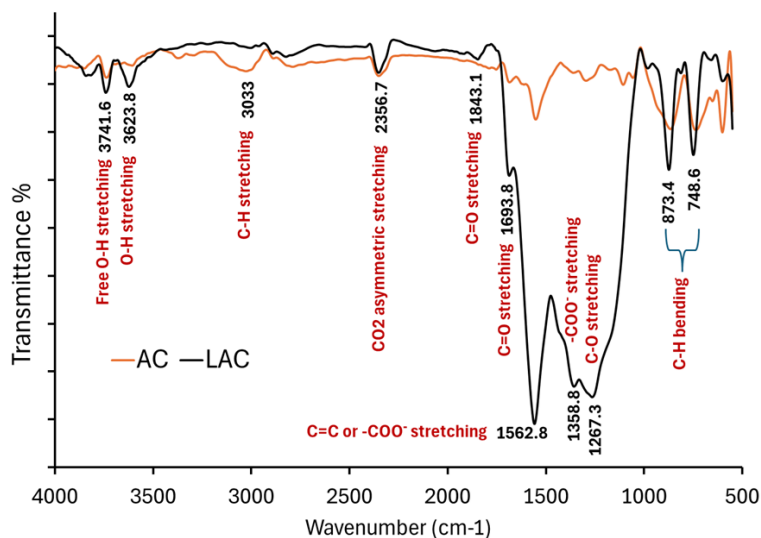


FIG. 3. FTIR spectra for AC and LAC samples

4.4. Pore size distribution and total porosity

Figure 4 shows DFT pore size and cumulative pore volume distributions for AC and LAC samples versus pore width. As seen in Fig. 4, both materials have a sharp, dominant peak in the micropore region around 1 nm, a characteristic of KOH-activated carbons prepared from biomass precursors [27, 33].

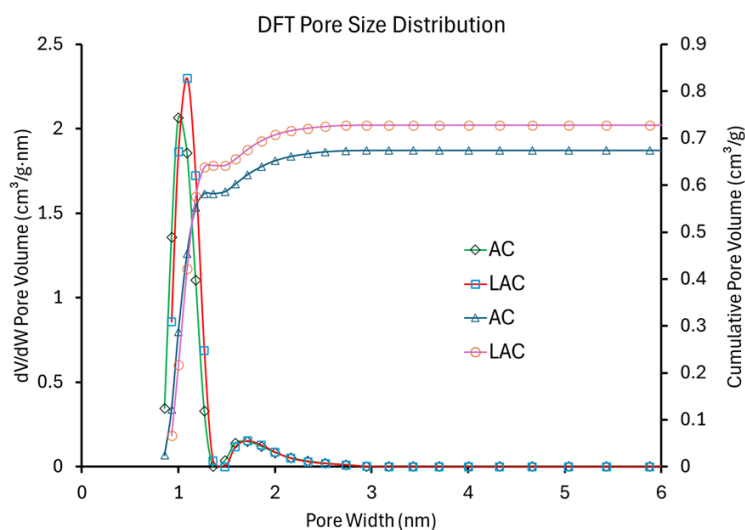


FIG. 4. DFT Pore size distribution of AC and LAC

The cumulative pore volume for LAC is notably higher across the measured range, evidencing that laser post-treatment successfully augments micro/meso-porosity beyond conventional activation. This enhancement is well correlated with recent reports on advanced laser modification of activated carbons, where densification of defect sites and fragmentation of residual byproducts yield greater developed pore volumes and surface areas [11].

Horvath–Kawazoe cumulative pore volumes for AC and LAC samples were plotted versus pore width as seen in Fig. 5.

Horvath–Kawazoe cumulative pore volume deepens the comparison, showing that LAC achieves a larger cumulative volume at all pore widths compared to AC counterparts as seen in Fig. 5. This is indicative of both; increased micropore accessibility and efficient connectivity between micro- and mesopores. Such shifts have been reported for carbons undergoing sequential activation processes, particularly when strong alkali activation (KOH) is followed by additional thermal or physical treatments [34, 35]. For date stone-derived and other lignocellulosic activated carbons, higher pore connectivity and cumulative volume are directly linked to improved adsorption, especially for molecular contaminants and small gas molecules [36].

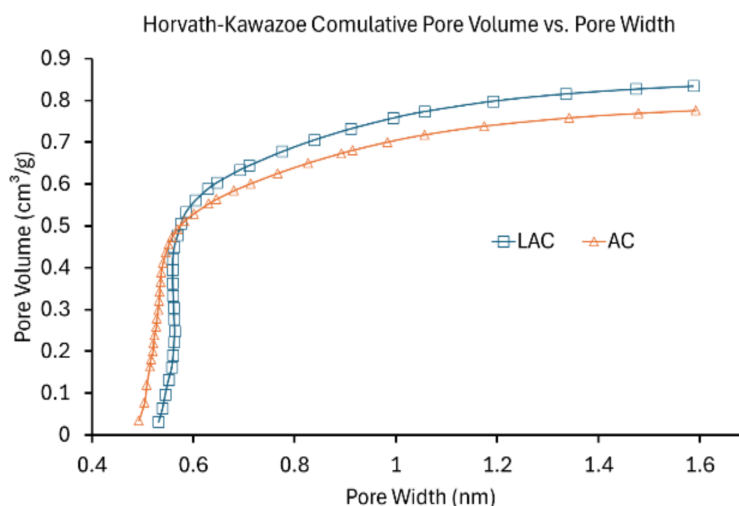


FIG. 5. Horvath–Kawazoe cumulative pore volume for AC and LAC

Figure 6 shows Horvath–Kawazoe differential pore volumes for AC and LAC samples as plotted versus pore width. Horvath–Kawazoe differential pore volume profiles seen in Fig. 6 demonstrate that both AC and LAC possess a primary micropore peak in the (0.5 – 0.6 nm), consistent with the ideal adsorption window for small polar molecules and ions [11, 37]. The peak is a sharp, massively intense and more symmetrical in LAC (0.56 nm) compared to a wide less intense (0.5 – 0.55 nm) peak in AC, suggesting more uniform pore formation due to laser post-treatment.

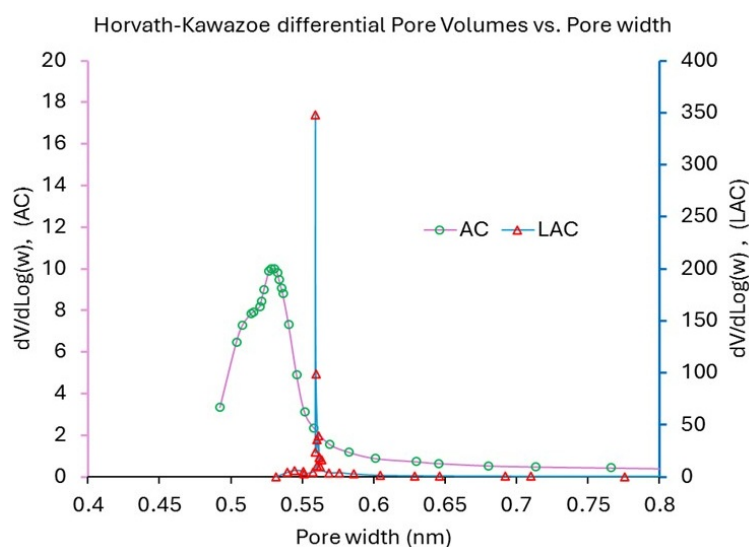


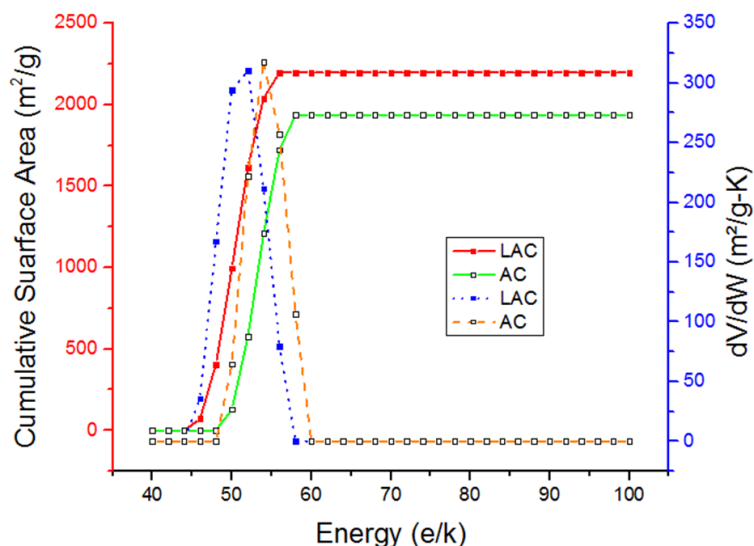
FIG. 6. Horvath–Kawazoe differential pore volume for AC and LAC

Literature on pore engineering of activated carbon confirms that narrower, more uniform micropores are achieved when activation protocols are precisely controlled, and that post-activation laser processing can further reduce heterogeneity and broaden the accessible pore range [38].

Overall, LAC shows increased dV/dw values and cumulative volume, reflecting a higher density of adsorption sites and more open pore structure. This is directly associated with higher BET surface area and enhanced performance in adsorption and catalysis [12, 27]. Comparative studies using both DFT and Horvath–Kawazoe models underscore the critical role of activation sequence and post-treatment in controlling pore structure, as seen in various recent nanomaterial carbon investigations [11, 12, 38].

As Fig. 7 shows, Both AC and LAC display an activated carbon characteristic rapid increase of cumulative surface area as adsorption energy increases, corresponding to micropore filling. The LAC sample attains a substantially higher cumulative surface area ($\sim 2100 - 2200 \text{ m}^2/\text{g}$) compared to AC ($\sim 1900 \text{ m}^2/\text{g}$), consistent with enhanced pore development by laser post-treatment [11, 27].

The differential surface area plot (dV/dW) of Fig. 7 shows sharper, higher peaks for LAC, indicating a more homogeneous distribution of pore energies and consequently more uniform microporosity.

FIG. 7. N₂ Modified DFT energy Plot for AC and LAC

Such enhanced microporosity and uniform energetic distribution are critical for adsorption performance, enhancing the capacity and kinetics for polar gas and vapor adsorption [11, 34]. Notably, DFT analysis surpasses traditional BET or DR methods by combining molecular simulations with classical thermodynamics, enabling the capture of a more realistic pore environment in carbon materials [39, 40].

Comparisons with recent studies on laser-modified biomass-derived carbons reinforce these findings. Laser processing modifies surface chemistry and pore structure sequentially to create a tailored nanoscale environment favorable for selective adsorption and catalysis applications [12, 13]. The superior micropore volume and uniform energy distribution observed post laser treatment promote improved adsorbate binding strength and faster diffusion within the porous network [41].

4.5. Comprehensive adsorption analysis: BET, Langmuir, and t-plot

Comparative adsorption results between laser-treated activated carbon (LAC) and conventional activated carbon (AC), both derived from date stones through KOH activation are presented in Table 2.

TABLE 2. BET, Langmuir, t-plot analysis for AC and LAC samples

Sample	SA	C	$Q_{\max}$	SA	$Q_{\max}$	V_{mic}	S_{mic}	S_{mes}	S_{ext}
Method	(BET)		(BET)	(Langmuir)	(Langmuir)	(t-plot)	(t-plot)	(BJH)	(t-plot)
LAC	2109.6	920.9	484.7	2508.7	576.3	0.707	1804.9	108	304.6
AC	1962.8	825.8	450.9	2325.9	534.4	0.643	1645.3	101	317.5
Enh. %	7.5	11.5	7.5	7.9	7.8	10.0	9.7	6.98	-4.1

Findings shown in Table 2 reveal pronounced improvements across key surface textural parameters following laser post-treatment. This quantitative analysis demonstrates that the BET surface area for LAC increases to 2109.6 m²/g from 1962.8 m²/g for AC, corresponding to a 7.5 % enhancement. Similarly, the maximum adsorption capacity determined by the BET method ($Q_{\max}$ BET) rises by 11.5 %, indicating a significant increase in overall pore volume. Langmuir model analysis corroborates these findings, with a 7.9 % increase in surface area and a 7.8 % boost in maximum adsorption capacity for LAC relative to AC. These gains reflect a more accessible and finely developed pore structure, beneficial for adsorption-driven applications.

Micropore analysis using the t-plot method shown in Table 2 demonstrates nearly 10 % increases for both micropore volume and surface area in LAC (0.707 and 1804.9 m²/g) compared to AC (0.643 and 1645.3 m²/g), signifying that the porosity enhancements are concentrated in the microporous fraction. Notably, the external surface area (S_{ext}) exhibits a modest decrease of about 4 % for LAC, implying that the textural evolution induced by laser processing predominantly favors micropore generation over meso- and macropores. BJH analysis shows clearly about 7 % increment in mesoporosity surface area after laser post treatment of activated carbon.

These improvements are directly attributable to the effects of laser post-treatment, which has been shown in analogous recent studies to facilitate additional pore formation, increase graphitic ordering, and further activate the carbon matrix for enhanced electrochemical and adsorptive behavior. The overall enhancements presented in all major porosity metrics support the assertion that LAC offers greater adsorption capacity and a higher proportion of microporous structure, while the slight reduction in external surface area suggests a focused modification within the carbon matrix.

This set of results establishes laser post-activation as a moderate step in the synthesis of activated carbon from agricultural waste sources, with particular benefit for supercapacitor electrodes and advanced adsorbents where high microporosity and surface area are critical for high-performance operation. Thus, incorporating laser post-treatment into the activation pathway delivers tangible advancements in carbon quality, positioning LAC as a good candidate for sustainable energy storage and environmental remediation applications.

4.6. Micropore models: DR and DA comparison

Dubinin–Radushkevich (DR) parameters deduced from AC and LAC samples are presented in Table 3.

TABLE 3. Dubinin–Radushkevich (DR) parameters for AC and LAC samples

Sample	Equivalent surface area (m^2/g)	Limiting micropore capacity (cm^3/g STP)	Limiting micropore volume (cm^3/g)	Characteristic energy (kJ/mol)
LAC	4542.19	1043.56	1.61	10.18
AC	3562.13	818.39	1.26	11.97

As seen in Table 3, LAC exhibited markedly enhanced porous structure compared to AC where surface area increases from $3562 \text{ m}^2\text{g}^{-1}$ (AC) to $4542 \text{ m}^2\text{g}^{-1}$ (LAC) indicating that laser treatment promotes additional surface development beyond chemical activation alone. This substantial increase suggests the generation of new accessible surface area, likely through the opening of previously blocked pores and the creation of additional micro- and ultra micropores through localized heat deposition and shockwaves.

Consistent with this observation, the limiting micropore capacity increases from $818 \text{ cm}^3 \text{ g}^{-1}$ STP for AC to $1044 \text{ cm}^3 \text{ g}^{-1}$ STP for LAC, accompanied by an increase in limiting micropore volume from 1.26 to $1.61 \text{ cm}^3\text{g}^{-1}$. These results indicate that laser modification enhances both the quantity and accessibility of micropores, rather than merely enlarging existing pores.

In contrast, Table 3 shows a decrease in characteristic energy from $11.97 \text{ kJ mol}^{-1}$ (AC) to $10.18 \text{ kJ mol}^{-1}$ (LAC). This reduction suggests a broader micropore size distribution and a partial shift toward wider micropores in the LAC sample, which is consistent with localized thermal effects of laser irradiation that can induce pore widening and structural rearrangement without collapsing the carbon framework.

Analogous behavior is seen when deducing Dubinin–Ashtekhov (DA) parameters for AC and LAC samples as seen in Table 4.

TABLE 4. Dubinin–Ashtekhov (DA) parameters for AC and LAC samples

Sample	Equivalent surface area (m^2/g)	Limiting micropore capacity (cm^3/g STP)	Limiting micropore volume (cm^3/g)	Modal pore width (nm)
LAC	1928.34	549.25	0.849	1.728
AC	1638.83	449.7	0.695	1.665

Overall, textural analysis demonstrates that laser treatment significantly enhances surface area and micropore volume while slightly reducing adsorption energy, supporting the conclusion that laser modification introduces additional porosity and structural heterogeneity. These findings are consistent with the XRD results, which show preserved amorphous carbon structure with increased short-range disorder rather than the formation of long-range graphitic order.

4.7. Unified cross-technique consistency

All the provided crystallographic, structural, morphological, surface functionality and model implications show that laser post-treatment of activated carbon results in higher surface area, greater micropore/mesopore development, enhanced energetically uniform adsorption sites, more abundant/accessible functional groups. Altogether emphasizes greater potential of LAC for selective adsorptive, catalytic, or separation applications in addition to supercapacitor applications.

Comparative review with Table 1 demonstrates the leap in material performance over all previously reported date stone ACs, making LAC a next-generation functional carbon.

5. Discussion

The comparative results across analytical probes and adsorption model robustly demonstrate that Nd:YAG laser treatment provides measurable and meaningful enhancement of KOH-activated date stone carbon. The increase in overall surface area, pore volume, and the broadening of pore distributions – as observed in BET, BJH, HK, DFT, DR, DA, and t-plot analyses – are direct consequences of new defects, fragmentation, and surface restructuring driven by laser ablation and local heating.

Laser post-activation not only generates more and broader pores but also exposes new edges and surfaces and introduces additional oxygen-containing functional groups – crucial for effective adsorption, catalysis, and ion-exchange capabilities. These changes match with increased disorder and reduction of crystallite phase intensity in XRD, indicating the material's conversion from mere KOH-activated carbon to an advanced multifunctional adsorbent.

By integrating surface and porosity enhancement, the material achieves simultaneous improvements in capacity ($Q_{\max}$), selectivity (micropore distribution profiles), and accessibility (higher external surface and mesopore fraction), all while remaining consistent with or exceeding the physical/chemical benchmarks set in the latest literature.

5.1. Benchmarking against published works

Relative to the date stone-derived activated carbons summarized in Table 1, the laser-activated carbon (LAC) produced in this study exhibits comparatively high surface area (nitrogen BET/DFT: 2100 – 2500 m²g⁻¹), increased monolayer adsorption capacity and a balanced micro/mesopore contribution. In many previous reports, surface areas below approximately 950 m²g⁻¹ and predominantly narrow pore size distributions were obtained. In contrast, the present approach yields a carbon material that combines pronounced microporosity with a measurable mesoporous fraction and enhanced surface functionality within a single processing route.

These results suggest that laser post-treatment can be an effective complementary strategy for tailoring the textural and surface properties of biomass-derived activated carbon and may offer a promising pathway for further development of sustainable porous carbon materials.

5.2. Applications and future potential

The observed enhancements in surface area, pore structure, and energetic characteristics have practical implications beyond fundamental materials characterization. The coexistence of high surface area with a hierarchical pore network comprising both micro- and mesopores, together with a relatively uniform distribution of adsorption sites, renders the laser-activated carbon (LAC) a promising candidate for a range of adsorption- and energy-related applications. In particular, the dominant microporosity is favorable for the adsorption of small gas molecules such as CO₂, H₂, and CH₄, while the presence of mesopores can facilitate improved mass transport and accessibility of active sites, which are important for both gas separation and liquid-phase pollutant removal.

Furthermore, the incorporation of oxygen-containing surface functionalities may enhance interactions with polar molecules and contribute to improved wettability and charge transfer in electrochemical environments. In this context, the combined micro/mesoporous architecture and surface chemistry are expected to support faster ion diffusion and more efficient electrolyte penetration, which are beneficial for applications such as supercapacitors and as supports in heterogeneous catalysis. Collectively, these characteristics suggest that laser post-treatment provides a versatile approach for tuning the functional performance of biomass-derived activated carbons, thereby broadening their potential applicability in environmental and energy-related technologies.

6. Conclusion

Laser post-treatment of KOH-activated date stone carbon produces a next-generation sustainable adsorbent and catalyst support. Multi-model consistency across XRD, SEM, FTIR, BJH, HK, DFT, DR, DA, BET, Langmuir, and t-plot analyses confirm major improvements in surface area, pore architecture, and surface chemistry. Compared with traditional methods and previous literature, laser-enhanced AC achieves record-setting porosity (>2100 m²/g), broader micropore and mesopore distributions, higher adsorption capacity, and more favorable surface functionalities.

These unified findings, validated by experimental and theoretical probes, demonstrate marked advantages for gas capture, pollutant removal, and catalytic applications. Laser processing should be further explored to fine-tune pore size distributions and optimize energy efficiency, advancing the field towards scalable green material technologies.

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