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**Original Research**

## **Synthesis and Physicochemical Characterization of Biomass-Derived Activated Carbon from *Moringa oleifera* Leaves**

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**Received:** 15/03/2026; **Accepted:** 21/09/2026; **Online Available:** 20/10/2026.

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### **Abstract**

Renewable biomass-derived activated carbon has been a subject of significant focus as an environmentally friendly alternative to conventional carbon-based products. The current study involves the preparation of activated carbon from *Moringa oleifera* leaves by using acid pretreatment, carbonization using heat and activation using potassium hydroxide (KOH). The physicochemical characterization of the activated carbon was performed using several characterization techniques such as X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), Field emission scanning electron microscopy (FE-SEM) coupled with Energy dispersive spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS). The XRD data showed that the activated carbon was mainly consists of amorphous carbon with disordered graphitic regions, based on the broad peaks in the diffractogram. The FTIR data showed the presence of hydroxyl, carbonyl and ether groups on the surface of the carbonaceous materials, which opens up the possibility for secondary interactions due to the polar nature of those functional groups. FESEM images indicated a rough, porous morphology, which was a result of the chemical activation process. The presence of carbon and oxygen were established as the two major elements which comprise the activated carbon using energy dispersive spectroscopy (EDS). Elemental analysis showed that the carbon content of the activated carbon was significantly high (83.62% estimated by weight), indicating high efficiency of carbonization of biomass prior to its activation occurred. The X-ray photoelectron spectroscopy analysis (XPS) further showed the presence of heteroatoms (N, P, K) on the surface of the carbon. These structural and compositional features suggest that activated carbon derived from *Moringa oleifera* leaves may prove to be a promising biomass-based carbon material in terms of applications in adsorption, catalysis and energy-related systems.

**Keywords**— *Moringa oleifera* leaves, Biomass-derived activated carbon, Chemical activation, Surface characterization, Elemental analysis, Sustainable carbon material, Renewable precursor

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## Introduction

Carbon-based materials were a subject of much interest in the field of modern-day materials science due to their versatile structures as well as diverse application possibilities. Conventional carbon allotropes (e.g., graphite and diamond) have been integrated into various industrial applications over the past centuries; nevertheless, the advent of newer advanced nanostructured carbon (e.g., graphene, carbon nanotubes, porous carbon) has greatly expanded how carbon can function as a material through its possible applications in energy storage systems, catalysis, environmental remediation and sensor technologies [1-4]. Moreover, due to their superior electrical conductivity, chemical stability and tunable surface chemistry, carbon-based materials are frequently used in electrochemical systems such as batteries and supercapacitors as well as in other energy storage applications due to these characteristics [5,6].

Electrochemical capacitors, often referred to as supercapacitors, have been developed into a viable option for energy storage due to their high power density, fast charge/discharge rate and long cycle life compared to traditional batteries [7,8]. The performance of supercapacitors is affected by the properties of the electrodes, including the presence of high surface area, suitable pore structure and good electrical conductivity which are crucial in determining the charge storage efficiency [9,10]. For these reasons, a number of different types of carbon-based materials including activated carbons, graphene and carbon nanotubes are currently being investigated as possible electrodes for high-performance supercapacitors.

Activated carbon continues to be one of the most common electrodes used due to its low cost, high chemical stability and well-developed porous structural properties [11]. Historically, activated carbon has been made from fossil fuel-derived products such as coal and petroleum pitch. However, due to growing environmental awareness and the demand for sustainable materials, interest has evolved in developing renewable, biomass-based carbon materials [12]. Biomass-derived materials are considered to be desirable because they are inexpensive, abundant and environmentally safe; they also commonly contain natural heteroatom species which can affect the electrochemical and chemical character of the resulting carbon materials [13].

Many sources of agricultural and biomass residues or waste from the agriculture have been discovered as sources of carbon for the manufacture of activated carbons, including rice husks, bamboo, coconut shells and tea waste [14, 15]. The organic composition of biomass consists primarily of cellulose, hemicellulose and lignin, which represent the predominant components of the structure of the carbonaceous material, facilitates the formation of carbon during the pyrolytic process, thereby producing porous carbonaceous structures through either a chemical or physical activation process.[16] This porous carbon material exhibits a high degree of potential application in a variety of applications such as adsorption, environmental remediation and in electrochemical energy storage systems.[17]

The plant *Moringa oleifera*, or "drumstick tree", is an evergreen tree native to tropical and subtropical regions which grows rapidly and has a range of uses. *Moringa* has been attracted for its nutritional and medicinal value as well as for its wide application as a food source, a source of pharmaceuticals and for water purification,[18]. The organic and mineral content of

Moringa's biomass has piqued researchers' interest as an attractive source to create porous carbon.[19].

Studies have shown that different parts of Moringa oleifera plant have been used to create activated carbon for use as electric energy storage materials. One area of research studies activated carbon from Moringa tree bark combined with tea waste that is used to create supercapacitor electrodes [20]. Based on these results, it can be concluded that Moringa-based biomass is suitable for renewable precursor materials to produce active carbon material. Chemical activation with potassium hydroxide (KOH) is one common method to create highly porous activated carbon materials. Potassium hydroxide reacts chemically with carbon during high-temperature activation, producing gaseous entities and metallic potassium intermediates which cause pore formation and rearrangements in the carbon framework. The activation process usually results in porous structures (micro and mesoporous) which are advantageous for adsorption-based and electrochemical-based applications.

Due to the large quantity of Moringa oleifera biomass which is available and its potential to be a renewable resource with favorable chemical properties, its use as a precursor for producing activated carbon has gained interest for additional investigation. The current research defines the production of activated carbon using Moringa oleifera leaves by combining the following methods: acid treatment, carbonization and KOH activation. After producing the activated carbon, characterization methods such as XRD, FTIR, FESEM, EDS, elemental analysis and XPS were used to study the structure and chemistry of the material. The results of this study reveal important information about the characteristics of activated carbon which is produced from Moringa oleifera leaves, showing that this biomass could be an environmentally friendly source of porous carbon materials that could potentially be used to store energy.

## **Materials and Methods**

### **Materials**

All reagents used in this study were obtained in analytical or reagent grades of quality and were used without any additional purification. Hydrochloric acid (HCl, 37%, Merck), potassium hydroxide (KOH, extra pure, Merck), sodium sulfate ( $\text{Na}_2\text{SO}_4$ , ACS grade, Fisher), tetraethylammonium tetrafluoroborate ( $\text{TEABF}_4$ , 99%, Sigma), poly(vinylidene fluoride) (PVDF, average molecular weight  $\sim 534,000$ , powder) (Fisher), N-methyl-2-pyrrolidone (NMP, ACS grade, Sigma), and acetonitrile (ACN, gradient grade, Sigma) were acquired from Sigma Aldrich. The DI water used for all experimental procedures was sourced from an R.O. water filtration system. Filtration methods were performed using Whatman Grade 1 qualitative filter paper (diameter 110mm). The pure graphite plates used as conductive substrates were obtained from OTOOLWORLD (USA) in a purity of 99.9%.

### **Synthesis of Activated Carbon**

In the Savar area of Dhaka, Bangladesh, adult leaves of Moringa Oleifera were harvested from local trees. The harvested biomass was manually sorted to remove debris from the bark, insects, and foreign material. After sorted, each leaf sample was thoroughly rinsed first with tap water, then multiple times with DI water, to remove any remaining dirt or surface

impurities. The clean leaves were cut into 2–3 cm segments and dried purely by use of solar energy for a total cumulative drying time of 72 hours.

After drying, the leaves were ground using a mechanical grinder and then subsequently sieved to create an even particle size. An acid pretreatment process was followed to remove any inorganic contaminants or soluble organics from the powdered leaves. For the acid pretreatment process, 10 gm of the ground leaves were refluxed with 25 mL of 1 M HCl at a temperature of 80 °C for 6 hours in a water bath with temperature controls. The resulting slurry was rinsed until all of the wash water has a neutral pH level. The acid treated biomass was then oven dried at 105 °C overnight to remove residual moisture loss.

For carbonization, the dried material was transferred into a horizontal tube furnace (Nabertherm, Germany) and heated under a continuous nitrogen (N<sub>2</sub>) stream. The heating rate was maintained at 10 °C/min until the temperature reached 800 °C, which was then sustained for 4 hours to generate biochar. This charred material was subsequently used for chemical activation.



**Figure 1.** Preparation of activated carbon derived from *Moringa oleifera* leaves collected at the campus of Gono Bishwabidyalay.

For chemical activation, the biochar was merged with potassium hydroxide (KOH) in a 1:1 weight ratio. KOH was dissolved in a little amount of distilled water and mixed into the biochar to create a uniform paste. The mixture was stirred at a rate of 400 rpm for 1 hour at a temperature of 80 °C to ensure an even distribution of the activating agent. It then dried overnight at a temperature of 105 °C. Following drying, the composite material underwent a second heating operation at a temperature of 850 °C for a period of 2 hours under a nitrogen atmosphere in order to complete the chemical activation process. Activated carbon prepared from moringa leaves (Moringa leaves derived activated carbon; MLAC) was thoroughly washed with distilled water until the pH reaches neutral, thereby removing any remaining chemicals or by-products from the process. Following purification, the MLAC was dried in an oven at 105 °C and stored in airtight glass containers for future physicochemical and electrochemical studies.

## Characterization

The physicochemical properties of the MLAC were systematically characterized using a suite of analytical techniques. The crystallographic structure of the carbon material was examined using X-ray diffraction (XRD), using a Thermo Scientific™ ARL Equinox 1000 diffractometer. The measurements were performed with Cu K $\alpha$  radiation ( $\lambda = 0.15406$  nm), operated at 40 kV and 60 mA, over a scanning range of 5° to 70° (2 $\theta$ ), allowing assessment of amorphous or graphitic nature of the material. To identify the surface functional groups, present on the MLAC, Fourier Transform Infrared Spectroscopy (FTIR; Frontier, PerkinElmer, UK), was conducted using a PerkinElmer Frontier spectrometer. Spectra were recorded over a range of 500 to 4000 cm<sup>-1</sup>, enabling the identification of key chemical bonds and oxygen-containing functionalities such as hydroxyl, carboxyl and carbonyl groups. The surface morphology and microstructural features of the samples was visualized using Field Emission Scanning Electron Microscopy (FE-SEM, JEOL-7610F, Japan) using a JEOL-7610F instrument. This was coupled with Energy Dispersive X-ray Spectroscopy (EDS) using a JEOL-JED2300 analysis station for elemental mapping and qualitative composition analysis. Elemental content, particularly carbon (C), nitrogen (N), hydrogen (H) and sulfur (S), was further quantified using a Unicube organic elemental analyzer (Germany), providing insight into heteroatom doping and the potential contribution of these elements to electrochemical behavior. Additionally, X-ray Photoelectron Spectroscopy (XPS, K-alpha, Thermo Scientific TM, USA) using a Thermo Scientific™ K-alpha spectrometer was used to investigate the chemical states and bonding environments of the surface atoms, confirming the presence of functional groups and heteroatom species.

## Result and Discussions

The morphological nature and crystalline phases of the MLAC were analyzed by X-ray diffraction (XRD) as presented in figure 2. The XRD pattern demonstrates two broad peaks centered at 2 $\theta \sim 25^\circ$  and 43° corresponding to the (002) and (100) crystallographic planes of the amorphous carbon, respectively. These features are characteristic of disordered (amorphous-type) carbon structures and suggest the presence of turbostratic graphite domains embedded in an amorphous carbon matrix. The (002) peak is typically attributed to the interplanar spacing of graphitic layers, whereas the (100) peak is associated with in-plane periodicity of carbon atoms within graphene. The broad nature and low intensity of these peaks confirm that the synthesized activated carbon lacks long-range crystalline order, consistent with a predominantly amorphous structure. This disordered arrangement is expected for biomass-derived carbons, which undergo partial graphitization upon pyrolysis. The presence of amorphous carbon is further supported by the absence of sharp, well-defined diffraction peaks characteristic of highly crystalline graphite. Amorphous carbon is advantageous in terms of pseudocapacitive behavior, as the disordered structure provides a larger number of defect sites and facilitates ion accessibility.

The formation of this amorphous and porous structure can be attributed to the natural composition of Moringa leaves, which contains biopolymers such as lignin, hemicellulose, and cellulose. Upon carbonization and acid treatment, these components undergo thermal degradation and rearrangement to form random graphitic fragments and a porous network.

Additionally, the carbonization process is influenced by the presence of metal ions and volatile compounds in the biomass, which promote pore formation and disrupt graphitic ordering.

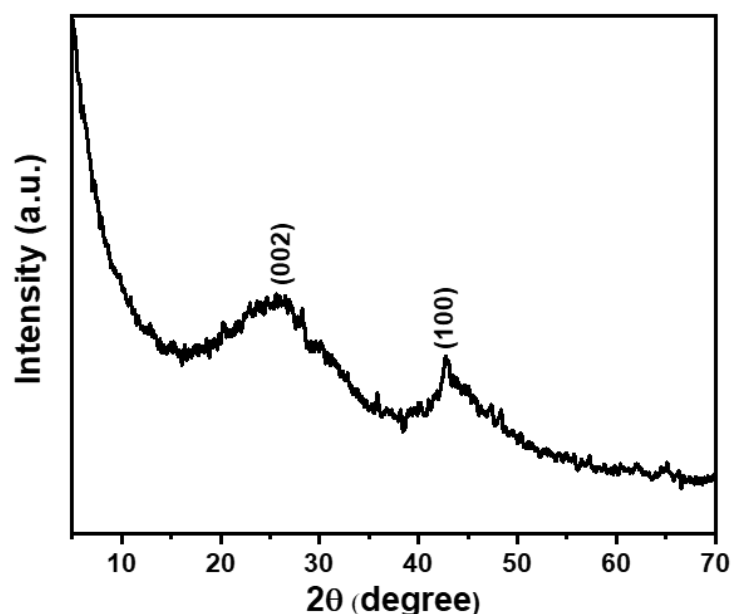


**Figure 2.** X-ray diffraction (XRD) pattern of Moringa leaves-derived activated carbon, showing broad peaks at approximately 25° and 43°, corresponding to the (002) and (100) planes of disordered carbon, indicative of an amorphous microstructure with graphitic domains.

The surface functional groups, chemical nature, and physical properties of MLAC were elucidated by Fourier Transform Infrared (FTIR) spectroscopy as illustrated in figure 3. A broad and intense absorption band is observed around 3450 cm<sup>-1</sup>, corresponding to O–H stretching vibrations, indicative of hydroxyl groups. A distinct peak is observed around 2350 cm<sup>-1</sup>, corresponding to Si–H stretching vibrations, suggesting the possible presence of Si-based residues. A band is observed around 1630 cm<sup>-1</sup>, corresponding to bending vibrations of –OH groups from physically adsorbed water. This band is also associated with the stretching vibrations of C=O bonds from aldehyde or carboxylate groups, indicating partial oxidation of the carbon structure.

A prominent band is observed at 1402 cm<sup>-1</sup>, corresponding to symmetric and asymmetric bending vibrations of C–H bonds, typical of aliphatic hydrocarbons. A strong and sharp peak is observed at 1115 cm<sup>-1</sup>, corresponding to asymmetric stretching of C–O–C linkages, indicative of the presence of ether or epoxide groups on the carbon surface. Several weak absorption bands are observed in the 550-900 cm<sup>-1</sup> range, corresponding to out-of-plane bending vibrations of aromatic C–H bonds, and are indicative of the presence of aromatic carbon structures. Overall, these surface functional groups are consistent with a chemically active and hydrophilic carbon surface.

The morphological features and pore architecture of the MLAC were extensively characterized by Field Emission Scanning Electron Microscopy (FESEM) as illustrated in figure 4. The FESEM micrographs of activated carbon clearly demonstrate that the surface

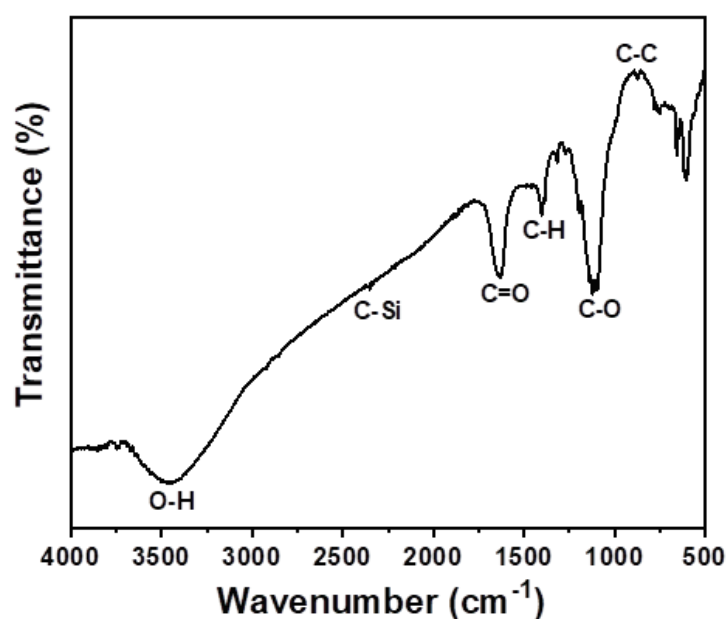


**Figure 3.** FTIR spectrum of Moringa leaves-derived activated carbon, showing characteristic absorption bands corresponding to hydroxyl (O–H), carbonyl (C=O), ether (C–O–C), aliphatic C–H, and silica-based functional groups, indicating a chemically active and hydrophilic carbon surface.

morphology of MLAC is highly irregular, rough, and porous. Numerous micro- and mesopores of varying shapes and sizes are distributed randomly across the carbon framework. This porous network is developed as a consequence of the chemical activation using potassium hydroxide (KOH), which played a pivotal role in introducing internal pores. During the thermal activation phase, KOH acted as an etching agent, reacting with the carbon matrix to generate gases such as  $H_2$ , CO, and  $CO_2$ . These gases escaped from the solid matrix, resulting in the formation of voids and channels throughout the carbon structure.

The harsh chemical and thermal treatment resulted in the degradation of hemicellulose, cellulose, and lignin components originally present in the Moringa leaves, leaving behind a carbonaceous skeleton with a high degree of structural disorder. The formation of cracks, cavities, and interconnected porous networks on the carbon surface suggests an effective activation mechanism that increases the specific surface area and pore volume, which are key parameters for applications such as adsorption and energy storage. Additionally, the surface roughness and fragmented texture reflect the collapse and rearrangement of plant-based microfibrils under high temperature, which contributes to the increase in active edge sites and exposed surfaces.

To confirm the morphological observations, Energy Dispersive X-ray Spectroscopy (EDS) was performed to elucidate the elemental composition, as presented in figure 5. The EDS spectrum shows dominant peaks corresponding to carbon (C) and oxygen (O), which are the principal elements of the activated carbon framework. The presence of magnesium (Mg) and potassium (K) is also apparent, with atomic percentages of approximately 2.45% and 1.70%, respectively.

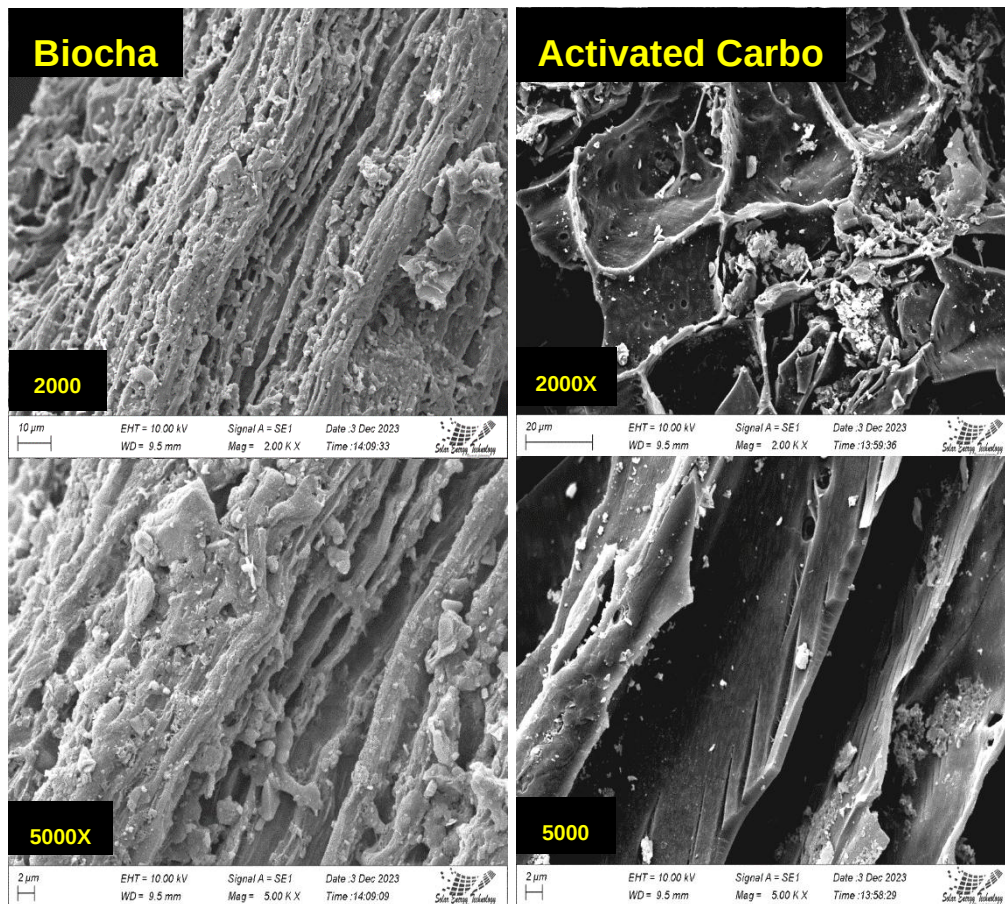


**Figure 4.** FESEM images of MLAC at varying magnifications showing an irregular and porous surface morphology developed during KOH activation.

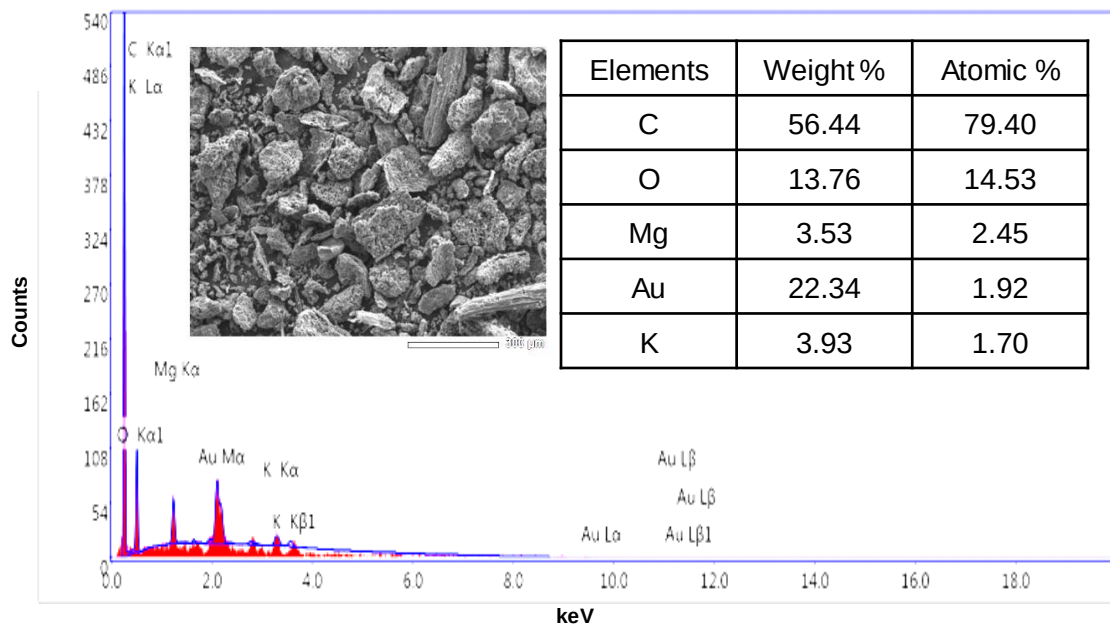


**Figure 5.** EDS spectrum and corresponding elemental composition table, confirming the presence of C, O, Mg, and K in the sample. The Au peak originates from the conductive coating applied prior to imaging.

Magnesium may originate from natural mineral content in the plant biomass, whereas residual potassium is a byproduct of the chemical activation process. These minor elements can potentially affect the surface chemistry, wettability, and catalytic behavior of the carbon. A distinct gold (Au) peak is also observed, which originates from the gold sputter coating applied to the sample surface for FESEM imaging. This thin conductive layer is applied to prevent charging effects under the electron beam. The elemental composition of the MLAC was quantitatively analyzed using an organic elemental analyzer to determine the proportions of carbon (C), nitrogen (N), hydrogen (H), and oxygen (O) present in the sample. The results are presented in table 1.

**Table 1.** Elemental composition of moringa leaves activated carbon

| <i>Sample</i> | <i>Carbon (wt%)</i> | <i>Nitrogen (wt%)</i> | <i>Hydrogen (wt%)</i> | <i>Oxygen (wt%)</i> |
|---------------|---------------------|-----------------------|-----------------------|---------------------|
| <b>MLAC</b>   | 83.62               | 0.03                  | 1.17                  | 14.50               |

The MLAC showed a very high carbon content of 83.62 wt%, which confirms the effective carbonization and thermal degradation of the lignocellulosic structure of the Moringa leaves during the pyrolysis and activation process. This high carbon percentage reflects the removal of volatile components such as hemicellulose, cellulose, and various organic moieties, resulting in a carbon-rich framework. High carbon content is critical for improving the electrical conductivity and structural integrity of activated carbon, and is beneficial for electrochemical applications such as supercapacitors and batteries. The oxygen content was recorded at 14.50 wt%, which is relatively moderate and indicates the presence of oxygen-containing surface functional groups such as hydroxyl (–OH), carbonyl (C=O), and carboxylic (–COOH) moieties. These functional groups enhance the surface polarity and wettability of the carbon material, facilitating efficient interaction with aqueous electrolytes. The presence of oxygen functionalities also promotes pseudocapacitive behavior through reversible redox reactions at the surface. The hydrogen content was relatively low at 1.17 wt%, suggesting minimal retention of hydrogen-rich functional groups or residual organic components after carbonization. A low hydrogen content is typically desirable in carbon materials, as it reflects a stable and less reactive surface. Interestingly, nitrogen was detected at a trace level of 0.03 wt%, which may originate from naturally occurring proteins or amino acids in the Moringa leaves. Even in small amounts, nitrogen dopants can enhance the electrical conductivity and electrochemical performance by facilitating Faradaic reactions. To obtain detailed insight into the surface chemical composition and bonding environment of the heteroatoms embedded in the porous activated carbon framework derived from Moringa leaves, X-ray Photoelectron Spectroscopy (XPS) analysis was carried out. The high-resolution XPS spectra provided valuable information about the chemical states of the constituent elements. The C1s spectrum (figure 6a) was deconvoluted into five distinct peaks centered at binding energies of approximately 284.5, 285.5, 287.3, 289.3, and 290.7 eV, corresponding to the presence of C–C (graphitic carbon), C–N (amines), C–O (hydroxyl/ether), C=O (carbonyl), and O–C=O (carboxylate) functionalities, respectively. These oxygen- and nitrogen-containing groups contribute to the hydrophilicity and redox activity of the carbon surface.

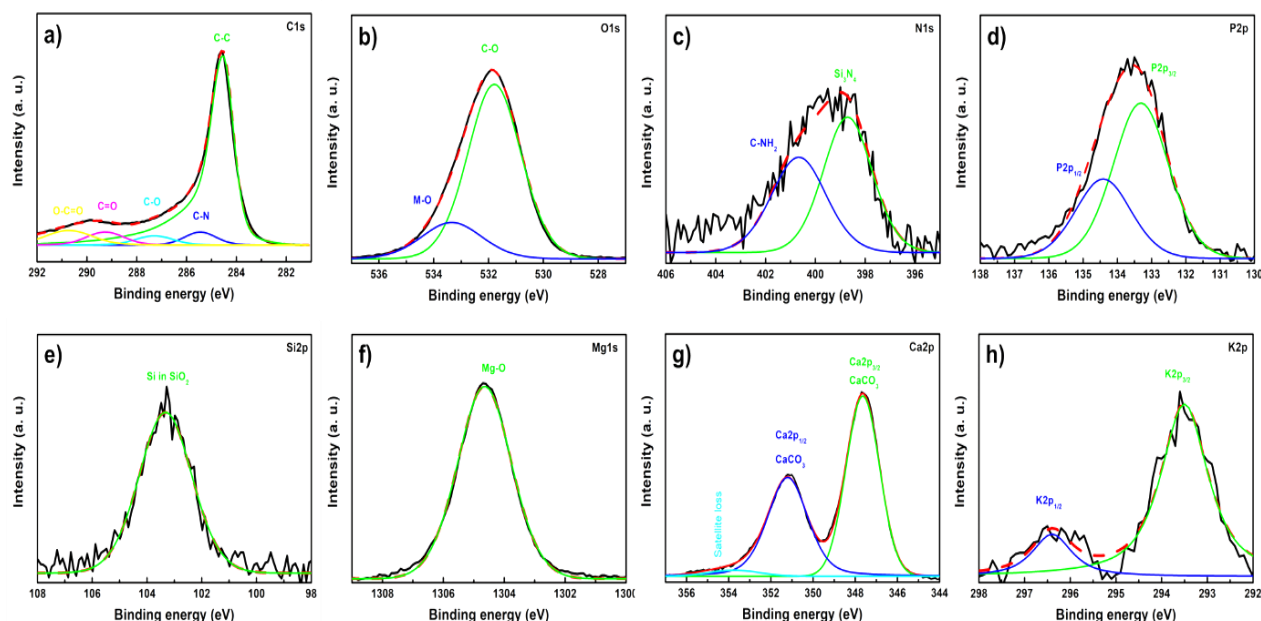


**Figure 6.** High-resolution XPS spectra of MLAC: (a) C1s, (b) O1s, (c) N1s, (d) P2p, (e) Si2p, (f) Mg1s, (g) Ca2p, and (h) K2p. These spectra illustrate the surface functional groups and elemental bonding states in the activated carbon matrix.

The O1s spectrum (figure 6b) was resolved into two main peaks located at 531.8 eV and 533.3 eV, corresponding to C–O bonds (phenols and ethers) and metal–oxygen species, respectively. The N1s spectrum (figure 6c) displayed two distinct peaks at 398.7 eV and 400.7 eV, attributed to Si–N bonding and terminal amino groups (C–NH<sub>2</sub>), respectively. The P2p region (figure 6d) revealed a well-defined doublet with peaks at 133.4 eV and 134.4 eV, assigned to the P2p<sub>3/2</sub> and P2p<sub>1/2</sub> orbitals, indicating the presence of phosphate or phosphonate groups embedded within the carbon matrix. The Si2p spectrum (figure 6e) exhibited a single prominent peak at 103.3 eV, corresponding to silicon dioxide (SiO<sub>2</sub>), which may act as a filler. A singlet peak at 1304.6 eV was observed in the Mg1s spectrum (figure 6f), indicating MgO or other Mg oxides. The high-resolution Ca2p spectrum (figure 6g) displayed two well-defined peaks at 347.6 eV and 351.1 eV, corresponding to Ca2p<sub>3/2</sub> and Ca2p<sub>1/2</sub>, respectively.

The peak separation of approximately 3.55 eV confirms the presence of calcium carbonate (CaCO<sub>3</sub>), a common residue from biomass precursors. The K2p spectrum (figure 6h) demonstrated a clear doublet at 293.5 eV and 296.4 eV, corresponding to K2p<sub>3/2</sub> and K2p<sub>1/2</sub>, respectively. The 2.9 eV energy splitting is characteristic of potassium ions (K<sup>+</sup>), which are likely derived from the KOH activating agent.

The presence of oxygen, nitrogen, phosphorus, and other inorganic dopants such as silicon (Si), magnesium (Mg), calcium (Ca), and potassium (K) within the carbon matrix significantly enhances surface wettability and electronic conductivity, making the material advantageous for applications in catalysis, adsorption, and energy storage.

## Limitations of the study

The study relies qualitatively on FE-SEM images to describe a "porous morphology." It lacks quantitative data on surface area pore volume and pore size distribution, which are typically measured via nitrogen adsorption-desorption isotherms (BET analysis). The paper characterizes the materials properties but does not test it in real-world applications. No data is provided regarding its efficiency in adsorption, catalysis or energy storage. The text does not mention optimization parameters. It is unclear how variations in carbonization temperature, heating duration or the ratio of KOH activator to biomass affect the yield and quality of the activated carbon. While XPS confirmed the presence of surface heteroatoms (N, P, K) the abstract and conclusion do not specify their atomic percentages or chemical states which heavily influence surface reactivity.

## Conclusion and Future Directions

Activated carbon was successfully prepared from *Moringa oleifera* leaves by using acid pretreatment followed by carbonization and chemical activation using potassium hydroxide. The structural and surface characteristics of the resulting material was investigated using several analytical techniques. X-ray diffraction analysis showed that the activated carbon was mainly consists of amorphous carbon with partially disordered graphitic regions. FTIR spectroscopy revealed the presence of oxygen-containing functional groups such as hydroxyl, carbonyl and ether species, which contribute to the chemical reactivity and surface polarity of the carbon material. Microscopic observations by using FESEM showed a rough and porous morphology, which was a result of the activation process, suggesting the formation of interconnected pores within the carbon framework. Elemental analysis showed that a high carbon content, demonstrating efficient conversion of the biomass precursor into carbon-rich material. In addition, XPS analysis showed several heteroatoms, indicating that the surface chemistry of the activated carbon is influenced by both the biomass composition and the chemical activation process. Overall, the results indicate that *Moringa oleifera* leaves can serve as a viable renewable precursor for the preparation of activated carbon. The structural features and surface functionalities observed in this study suggest that the material could have potential applications such as adsorption, catalysis and energy-related technologies. Further investigations, which will involve detailed porosity measurement and electrochemical evaluation, will assist in to better assess its suitability for such applications.

**Detailed Textural Characterization:** Conduct nitrogen physisorption (BET and BJH methods) to precisely determine the surface area total pore volume and micro/mesopore distribution of the activated carbon. Test the materials capacity to remove heavy metals, dyes or pharmaceuticals from wastewater through kinetic and isotherm modeling. Evaluate its performance as an electrode material in supercapacitors or lithium-ion batteries via cyclic voltammetry (CV) and galvanic charge-discharge (GCD) testing. Assess its efficiency as a catalyst or catalyst support in chemistry reactions. Perform studies varying the activation temperatures, residence times and chemical impregnation ratios to maximize the surface area and carbon yield.

Regeneration and Reusability Studies: Investigate the chemical stability and reusability of the activated carbon across multiple cycles to evaluate its economic viability, for industrial applications.

### Authors Contributions

Afroz Moutusi and Nilay Kumar Dey contributed to the conceptualization, study design, and writing of the draft manuscript. Most. Sabiha Islam Tithi, Apurbo Monidas, Farhana Afroze, Atkiya Anjum Nishat, Shuqria Alim and Beauty Akter were involved in sample preparation, activated carbon synthesis, and experimental work. Salwa Nailah Tanha, Nurunnahar Shuchi Hridoy Chandra Paul and Rehena Afroz Moutusi contributed to data collection, characterization, and analysis. Abdur Rahim provided scientific guidance and reviewed the methodology. Nilay Kumar Dey supervised the research, interpreted the findings, and reviewed and revised the manuscript. All authors discussed the results, reviewed the manuscript, and approved the final version for publication.

### Acknowledgements

We gratefully acknowledge the Department of Chemistry, Gono Bishwabidyalay, for providing laboratory facilities and continuous academic support throughout the research. Special thanks are also extended to the Bangladesh Council of Scientific and Industrial Research for their support with advanced instrumentation and technical analyses essential to this study.

### Conflict of interest

The authors declare that they do not have any conflict of interest.

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