Review:

Biomass-Derived Supercapacitors Supercharged with MXene Integration

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Abstract: *Biomass-derived carbon, obtained from renewable organic materials, offers several advantages, including sustainability, cost-effectiveness, and excellent electrochemical properties, such as high energy and power densities, adjustable morphologies, and cycling stability. However, the limitation of carbon-based materials can be addressed through surface modification with layered materials such as, layered double hydroxides, metal dichalcogenides, graphene, vanadium pentoxide and the new emerging material MXene. This review highlights techniques particularly heteroatom doping and chemical or physical activation to further enhance the electrochemical performance of biomass-derived carbon as supercapacitors. It also examines the synthesis of MXenes, two-dimensional transition metal carbides and nitrides, known for high conductivity, structural stability, and versatile surface chemistry. Despite these advantages, MXenes face challenges such as self-oxidation, self-discharging, and nanosheets restacking, which limit long-term stability. The effective strategies including surface and interlayer modifications and optimized synthesis route, are explored to significantly improve the electrochemical performance MXene-based composites. Additionally, the enrichment of biomass waste and the role of MXenes in electrical double-layer (EDLCs) and pseudocapacitance are emphasized, with MXene offering continuous electron transport channels, high oxidation resistance, and structural stability. Ultimately, integrating biomass-derived carbon with MXenes offers promising pathway to develop high-performance, sustainable supercapacitors for efficient energy storage solutions in future applications.*

Keywords: *biomass; energy storage; MXenes; supercapacitor*

■ INTRODUCTION

Energy is crucial for the development and survival of human beings. The use of different forms of energy to meet the surging demand for electricity is much higher than that of overall energy consumption [1]. Currently, fossil fuels, such as coal, unrefined oil and fossil gas, surpass 85% of the entire energy requisition. However, it is difficult to deal with the increasing demand for energy by solely relying on the limited and non-renewable reserves of fossil fuels. Moreover, it results in the emission of undesirable greenhouse gases, which leads to global warming and other environmental issues [2]. The United Nations highlights that fossil fuels are the primary driver of climate change, contributing to more than 75% of global greenhouse gas emissions and nearly 90% of CO_2 emissions [3-4]. Consequently, there is an increasing focus on exploring renewable energy sources, derived from naturally replenishing sources such as sunlight, wind, and water. These sources are integral in addressing the fossil fuel exhaustion crisis and the associated ecological consequences, driving a global shift towards sustainable energy solutions [5]. However, the intermittent nature of these sources presents challenges for maintaining a consistent and reliable energy supply. This underscores the critical need for advanced energy storage systems to bridge the gap and make renewable energy more feasible and reliable [6]. As a result, the demand for effective electrical energy storage solutions has become more critical than ever, as renewable energy sources transition from novelty to necessity [7-8].

Indonesia has a biomass energy potential of around 130 million tons annually, equivalent to 39 million tons of oil, primarily sourced from agricultural and forestry residues such as oil palm waste, rice husks, coconut shells, sugarcane bagasse, and sawdust [9]. Beyond power generation, this abundant biomass can be converted into high-value carbon-based materials such as activated carbon, biochar, and carbon nanotubes widely studied for their versatile applications [10]. Due to their high surface area, electrical conductivity, and environmental sustainability, these materials hold great promise for use in energy storage systems like supercapacitors and batteries [11]. With growing global demand for efficient and eco-friendly energy storage, the development of biomass-derived carbon materials presents a promising pathway for advancing supercapacitor technology, offering both environmental and economic benefits [12].

Storing electrical energy can be achieved via electrochemical or electrostatic energy storage mechanisms [13-14]. Batteries store high energy density but have reduced ability to deliver power rapidly, the restricted ability to endure repeated cycles and an abbreviated operational lifespan due to the physicochemical alterations happening within the electrodes and electrolytes during the charge-discharge process. As a result, batteries experience a drop in storage performance after 2–3 years, along with concerns about environmental hazards and human safety. Therefore, relying solely on batteries for energy storage is an impractical choice, especially when the power requirements of devices like smartphones and automobiles often exceed the capabilities of batteries to deliver [15]. On the other hand, capacitors offer rapid charging and discharging capabilities with high power density, making them suitable for applications that require quick bursts of energy. However, their energy storage capacity remains relatively low [3]. Combining the benefits of both capacitors and batteries, supercapacitors have taken center stage in electrical energy storage systems owing to their appealing attributes such as remarkable power density, quick charging/discharging ability, enduring resilience, and eco-friendly nature [16].

Integrating various layered materials offers a promising solution to enhance the performance of supercapacitors. Materials such as graphene and its derived forms like graphene oxide [17], reduced graphene oxide [18], transition metal dichalcogenides (e.g., MoS_2, WS_2) [19], MXenes (e.g., $Ti_3C_2T_x$) [20], and layered double hydroxides [21] provide high surface area, excellent electrical conductivity, and tunable interlayer spacing, which are essential for improving charge storage and ion transport [21-22]. Incorporating 2D materials into supercapacitor electrodes can significantly enhance the device's energy density, power density, and cycling stability. The unique properties of these materials enable better ion accessibility and faster ion diffusion, further boosting the overall performance of supercapacitors for high-efficiency energy storage applications [23]. While numerous 2D materials have shown potential in supercapacitor research, a significant challenge remains in balancing conductivity, ion accessibility, and structural stability within a single material system. This has prompted a growing research emphasis on MXenes, whose compositional diversity and surface chemistry tunability offer a uniquely adaptable platform to address these limitations [24].

Due to their unique structural properties, MXenes have emerged as one of the most promising materials for energy storage applications, particularly in supercapacitors. With their high surface area, excellent electrical conductivity, and tunable surface chemistry, MXenes offer significant advantages in charge storage and ion transport [25]. These materials demonstrate exceptional power and energy densities, long cycle life, and rapid ion diffusion, making them ideal candidates for next-generation energy storage devices [24]. However, by integrating this biomass-derived carbon with MXenes $Ti_3C_2T_x$ [26-27], $V_4C_3T_x$ [28], and Cr_2CT_x [29], a family of two-dimensional (2D) materials known for their remarkable electrical conductivity, large surface area, and tunable surface chemistry. Swami and co-workers reported extraordinary surface enhancement in $Ti_3C_2T_x$, and its integration with mesoporous carbon derived from alginate acid achieved 97.5% stability performance for 60,000 cycles [30]. Song et al. [31] also reported that integrating activated carbon fiber from wood successfully enhanced the interlayer spacing with $Ti_3C_2T_x$ as a flexible free binder electrode for supercapacitor application. Development of carbon derived from biomass and numerous MXene substrates demonstrated a unique characteristic that enhances the electrochemical performance of biomass carbon by increasing the electroactive surface area and retaining its capability, stability, sustainability, and cost-effectiveness [32].

The continual increase in global energy demand and the predominant reliance on non-renewable and environmentally detrimental energy sources highlights the urgent need to advance sustainable and efficient energy storage technologies. As depicted in Fig. 1, supercapacitors present a promising solution due to their inherently high-power density, rapid charge-discharge rates, and superior cycling stability compared to conventional batteries and capacitors. Despite these advantages, critical limitations such as relatively low energy density, cost-intensive materials, and long-term stability constraints must be addressed to enable their widespread application. Future efforts should be directed towards the rational design and integration of advanced materials such as nanostructured hybrids and layered systems to enhance electrochemical performance while ensuring scalability and environmental compatibility. These advancements are expected to position supercapacitors as a pivotal component in next-generation energy storage systems, supporting the transition toward more sustainable energy infrastructures [33-34].

■ SUPERCAPACITORS

Supercapacitors (electrochemical capacitors, electric double layer capacitors or ultra-capacitors) are energy storage devices that can store energy by electrostatic means or/and faradic electrochemical means. They are the optimal choice for the systems that undergo frequent charge and discharge cycles at high current and short duration [35]. For applications where there is a need for high power but low energy density, Supercapacitors shine as a top-notch option, especially in conditions such as frigid temperatures, regenerative brake systems, and power surges. Supercapacitors are at the forefront of a global energy revolution by powering hybrid electric vehicles, ensuring efficient wind and solar energy storage, and integrating seamlessly into transportation systems like trains and airborne vehicles. This trend is driving a remarkable annual revenue growth of 19.8% with an astonishing sixfold expansion anticipated soon.

Supercapacitor Components and Configuration

A supercapacitor incorporates two electrodes with ample surface area separated by a thin ion-permeable

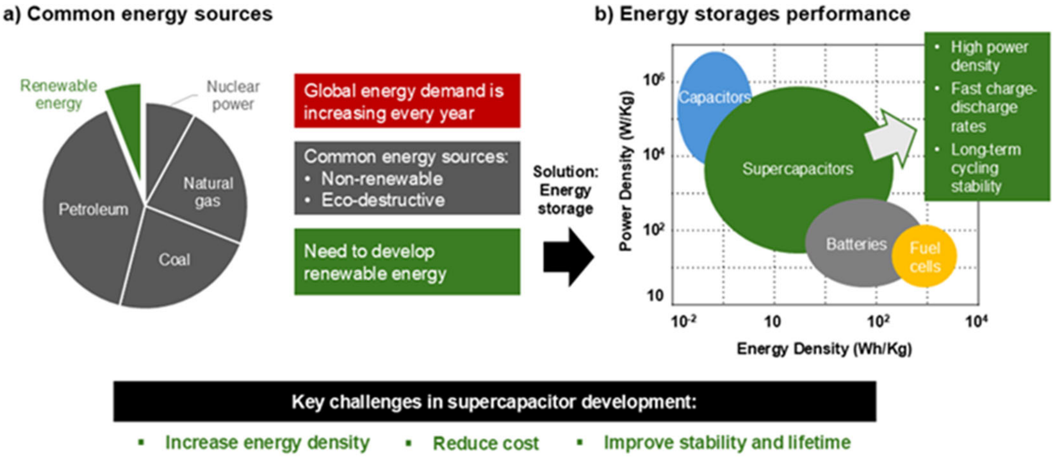

Fig 1. (a) A pie graph of common energy sources and (b) several examples of energy storage devices and their performance based on energy and power density

membrane that allows movement of ions but prevents short circuits within the electrode pair and is immersed in an electrolyte. The electrode material is deposited on a current collector, which connects the external circuit with the electrodes and provides mechanical support. When a voltage is applied across the electrodes, the ions in the electrolytic solution get attracted towards the oppositely charged electrodes, forming an electric double layer which stores the energy through charge accumulation at the electrode-electrolyte interface [36-37].

The Principal Charge Storage Mechanism of Supercapacitors

Supercapacitors can be classified into three classes based on their mechanism for storing electrical charges: electrical double layer capacitors (EDLC), pseudocapacitors, and battery hybrid supercapacitors, as illustrated in Fig. 2. Since ion binding and unbinding at the electrode-electrolyte junction are reversible, EDLCs typically store charge electrostatically. Carbonaceous electrode materials used in EDLCs include activated carbon, graphene, and nanostructured carbon aerogels [38-39]. An electric double layer forms at the borderline between the terminals and the medium in EDLCs, which acts as the insulating medium. This behavior is similar to conventional capacitors because it doesn't rely on Faraday processes to store energy [40-41]. Pseudocapacitors, commonly called redox capacitors, store charge using Faradaic processes [42]. Additionally, the pseudocapacitance originates from electron shift (oxidation-reduction reaction), which proceeds at the electrode's surface and resembles the charging and discharging of a battery. The use of both EDLCs and pseudocapacitors in combination can improve productivity overall, increase their power output, and boost energy storage [43].

Symmetric supercapacitors

Symmetric supercapacitors are the conventional and fundamental models that utilize a central separator serving as a plane of symmetry, retaining electrodes on both ends that are perfectly identical. As the electrodes act as mirror images of each other, the electrical characteristics of the two plates work in an opposing manner. For producing such capacitors, a substantial variety of carbon-based materials combined with conductive polymers or metal oxides have been employed serving as electrode components [44-47]. Since the electrodes in symmetric supercapacitors are similar, the voltage range of these supercapacitors is constrained by the electrode material’s voltage limits, limiting the power density and energy density [48].

Asymmetric supercapacitors

In asymmetric supercapacitors, both electrodes are not identical and are made of different materials [46-47]. Hence, four potential combinations are feasible i.e.,

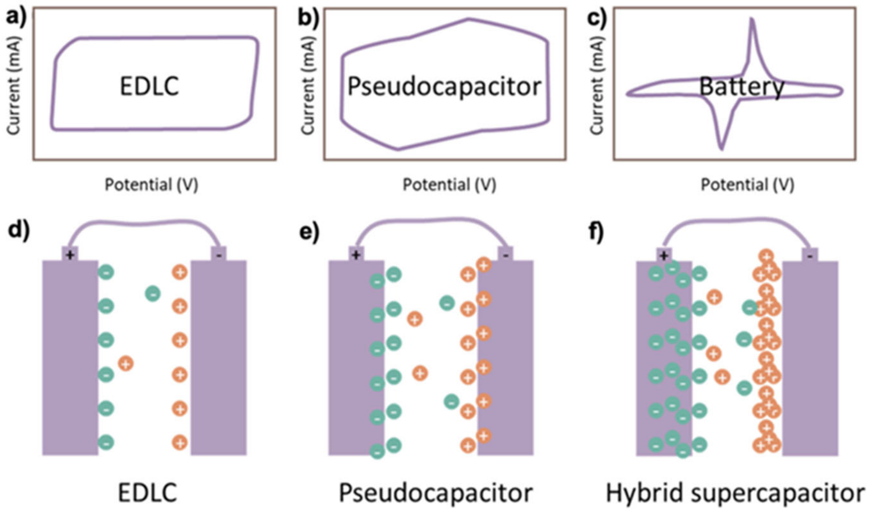

Fig 2. (a-c) CV profiles and (d-f) charge storage mechanisms of EDLC, pseudocapacitor, and hybrid supercapacitor; adapted from Zhu et al. [43], under the terms of the Creative Commons Attribution License (CC BY)

(i) both electrodes utilize distinct EDLC materials; (ii) the oxidation electrode is made from an electrostatic capacitor material, the reduction electrode is a faradaic capacitor material; (iii) the proton conductive electrode employs electrochemical capacitor material, the electron conductive electrode is a double-layer capacitor material; or (iv) both electrodes are crafted from distinct pseudocapacitive materials [49]. A wide array of carbon-based materials combined with metal oxides, metal hydroxides, metal carbides, metal phosphides, or conductive polymers, and metal compounds paired with conductive polymers are utilized as electrode materials for such supercapacitors [50]. As they combine the advantages of EDLC and supercapacitors, they offer enhanced energy and power density along with a prolonged cycle stability, making it a significant domain of exploration in supercapacitors [48,51].

Hybrid supercapacitors

The advantages of batteries and capacitors, including a high voltage range, a substantial capacitance, and a decent energy density, are harmoniously integrated by the hybrid supercapacitor [52]. The critical performance characteristics of hybrid supercapacitors, such as their charge-discharge rates, power intensity, intrinsic resistance, and durability, are influenced by the materials used in the battery electrodes [46]. To increase the energy and power density of hybrid supercapacitors, innovative composite electrode materials with significant specific capacitance, high working voltage, superior specific power, and longer cycle life have been designed [52-53].

■ BIOMASS AS A SUSTAINABLE ENERGY SOURCE

According to the International Energy Agency, biomass refers to biotic materials such as organic products, agricultural residues, and industrial or municipal waste derived directly or indirectly through photosynthesis [54]. In addition to serving as a renewable carbon source, biomass contributes to global waste reduction by valorizing organic waste streams [55]. In recent years, biomass, particularly lignocellulosic materials, has attracted significant attention as a sustainable carbon source for energy storage applications. The complex relationship between biomass composition and its resulting electrochemical performance has led researchers to explore various precursors and activation methods to enhance supercapacitor behavior. Wood-derived fibers, cotton stalks, agricultural residues, and plant-based wastes have shown remarkable potential when appropriately processed into porous carbon structures [56]. With these biomass sources, the synthesis of carbon-based electrodes has been done with various structures of carbon. The source biomass and the activation route employed strongly influence the performance of biomass-derived carbon materials for supercapacitors as highlighted in Table 1, a wide range of biomass sources that are processed through several techniques exhibit tunable porosity, large surface areas, and outstanding electrochemical properties. Such findings underscore the strategic value of converting renewable biomass into high-performance electrode materials, offering sustainable and cost-effective solutions for next-generation energy storage systems.

Influence of Biomass Composition on Carbon Properties

Biomass feedstocks can be broadly classified into plant-based and animal-based sources. Plant biomass primarily consists of structural components such as cellulose, hemicellulose, lignin, and plant fibers, while animal-derived biomass includes proteins, minerals, and polysaccharides such as chitosan and chitin [68-69]. In Fig. 3, the characteristics of each plant biomass component are described. In the plant biomass, the composition of biomass plays a critical role in determining the structural and electrochemical characteristics of the carbon materials. Cellulose, being a highly crystalline polysaccharide consisting of *D*-glucopyranoses, decomposes at higher temperatures (300–400 °C), resulting in carbon materials with high surface area and microporosity. This is ideal for high-energy density supercapacitors, as the micropores provide many sites for ion storage [70]. The oxygen-containing functional groups in cellulose are eliminated during pyrolysis, enhancing the ion-accessible pathways and contributing to the capacitance of the supercapacitor [71].

Table 1. Biomass sources for supercapacitor electrodes

Biomass source	Activator (Temp.)	Carbon structure	Key Findings			
			Surface area (m^2 g^{-1})	Specific capacitance (F g^{-1})	Electrolyte	Cyclic stability
Wood [57]	Steam (850 °C)	Hierarchical porous structure	3223	280.00 at 0.5 A g^{-1}	1 M H_2SO_4	99.30% (2000 cycles)
Cotton [58]	H_3PO_4 (800 °C)	Disordered and interconnected pore system	1481	114.00 at 0.5 A g^{-1}	1 M Et_4NBF_4	95.30%
Hemp [59]	$KMnO_4$ (600 °C)	Optimized hierarchical porous structure	1193	255.50 at 1 A g^{-1}	6 M KOH	97.80% (100,000 cycles)
Bamboo [60]	$KHCO_3$ (800 °C)	3D structure with micro, meso, and macropores	1893	253.00 at 0.5 A g^{-1}	6 M KOH	~100.00% (10,000 cycles)
Banana [61]	$ZnCl_2$ (800 °C)	Micrometer-sized tube-like structure	1097	74.00 at 0.5 A g^{-1}	1 M Na_2SO_4	~88.00% (500 cycles)
Corn stalk [62]	NaCl, KCl (800 °C)	Porous, thin carbon sheets	2139	317.00 at 1 A g^{-1}	6 M KOH	>93.00% (10,000 cycles)
Sugarcane bagasse [63]	NaOH (70 °C)	Well-developed pore structure	3135	410.50 at 0.5 A g^{-1}	6 M KOH	~100.00% (10,000 cycles)
Palm oil [64]	KOH/CO_2 (800 °C)	Self-adhesive carbon grains	1704	150.00 at 0.5 A g^{-1}	1 M H_2SO_4	–
Rice husks [65]	KOH (800 °C)	Enhanced hierarchical porous structure	3145	367.00 at 0.5 A g^{-1}	6 M KOH and 1.5 M Et_4NBF_4	>90.00% (30,000 cycles)
Pinecone [66]	KOH (750 °C)	Highly interconnected porosity	3950	198.00 at 0.5 A g^{-1}	1 M $LiPF_6$	~90.00% (20,000 cycles)
Foxtail millet husk [67]	KOH	Well-developed porous structure	–	82.94 at 0.5 A g^{-1}	1 M Na_2SO_4	94.89% (5000 cycles)

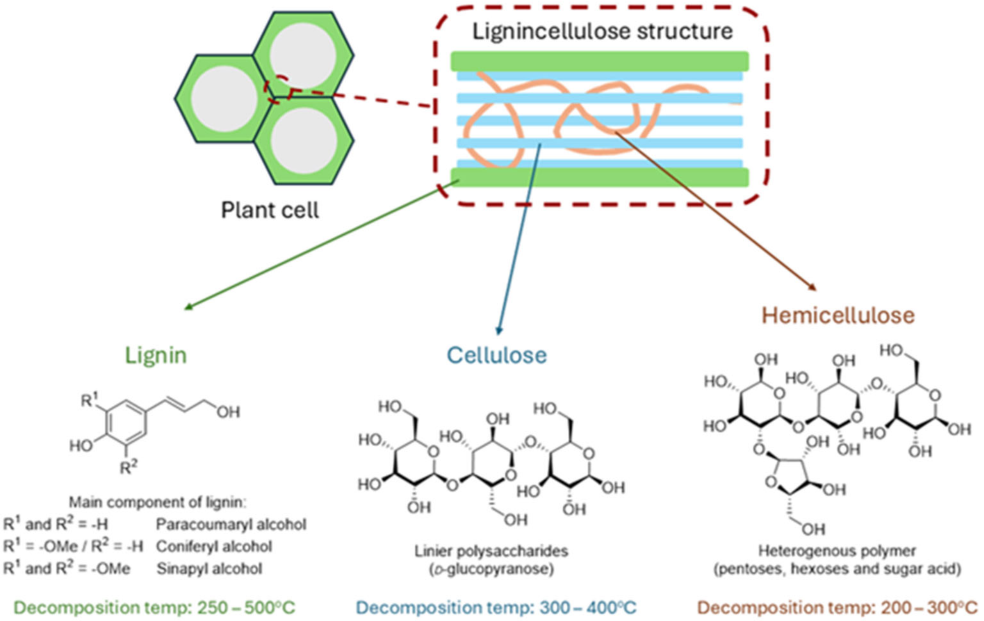

Fig 3. Characteristics of each plant biomass component

In contrast, hemicellulose is more amorphous and less thermally stable, consisting of several saccharides such as pentoses, hexoses, and sugar acids, decomposing at lower temperatures (~200–300 °C), forming disordered carbon structures. While this results in lower carbon yield and reduced electrical conductivity, the enhanced porosity improves charge storage capacity, which is particularly useful for applications requiring high energy density. However, it may limit rate performance [72].

Lignin, a highly cross-linked aromatic polymer consisting of some aromatic alcohol functional groups (*p*-coumaryl, coniferyl, and sinapyl alcohol), decomposes over a broader temperature range (250–500 °C) and forms graphitic carbon. This contributes to superior electrical conductivity and mechanical stability but results in a lower surface area than cellulose and hemicellulose. As a result, lignin-derived carbons are particularly suitable for high-power supercapacitors that require rapid charge/discharge cycles, as their conductivity allows for faster electron movement during operation [73].

Structure and Electrochemical Properties of Biomass Sources

The utilization of each biomass component affects the structure of the synthesized carbon. By using different biomass components, the porosity of the carbon can be tuned between microporous, mesoporous, and nanoporous structures. Moreover, the composition of each biomass component or their mixtures also influences the porosity and surface area of the resulting carbon. Higher cellulose content increases surface area and enhances microporosity, making it ideal for supercapacitors focused on high energy density. Higher lignin content, on the other hand, enhances conductivity and mechanical stability, which is beneficial for high-power applications [74]. The role of hemicellulose is to increase porosity, improving charge storage without sacrificing conductivity. Thus, a balanced ratio of these three components can lead to optimal performance for supercapacitors requiring high energy storage and power output [43]. Mineral content in biomass also plays an important role. Biomasses with higher mineral content (e.g., K, Na, Mg) can act as natural activators during pyrolysis, aiding pore formation. However, excessive mineral content can reduce conductivity, requiring post-treatment (e.g., acid washing) to remove residual minerals and prevent performance degradation [75].

Deng et al. [76] show that the composition of biomass, particularly the ratio of cellulose, hemicellulose, and lignin, significantly affects the structure of derived carbon materials. Cellulose and hemicellulose, with their high oxygen content, form micropores during pyrolysis as these groups are eliminated, while lignin's aromatic structure leads to the formation of nonporous carbon. The study further demonstrates that a mixture of cellulose, hemicellulose, and lignin (with less than 50% lignin) creates a three-dimensional porous structure, with macropores, mesopores, and micropores, primarily when $KHCO_3$ is used, aiding in macropore formation.

Another important parameter for controlling the porosity of carbon is the activation process (either physical or chemical). However, the results are generally inconsistent due to unidentified variables (variation in both biopolymer and impurity content, activation agents and/or carbonization conditions), even with many results reported [77]. Several examples of carbon derived from biomass sources are graphene, carbon nanotubes (CNTs), multi-walled CNTs (MWCNTs), and quantum dot single carbon (QDSCs). To effectively utilize these carbon materials for supercapacitor electrode applications thorough understanding of their physicochemical properties and structure performance relationships is essential [77].

Biomass-Derived Carbon for Supercapacitors

Using biomass products as precursors for synthesizing porous carbon compounds is essential for green chemistry since it enhances environmental sustainability. This notion has gained widespread attention because of the inherent benefits of biomass, which include high carbon content, natural abundance, environmental friendliness, and low cost [78-79]. Because most untreated biomass materials are hard and contain a lot of contaminants, they are not appropriate for direct use as electrode materials for electrochemical energy storage systems. A fair degree of graphitization, an acceptable specific surface area, a balanced pore distribution, and favorable phase/surface chemical characteristics will alter the conductivity and ion-diffusion rate of carbon materials in electrolytes, resulting in electrochemical property differences. A feasible processing approach is thus of high strategic importance to produce low-cost and efficient biomass carbon electrode materials. Many synthesis procedures have been designed to facilitate the regulated preparation of biomass-derived carbon compounds as shown in Fig. 4 [80].

Among the reported strategies, three primary synthesis routes have been widely used, including carbonization (such as pyrolysis and hydrothermal methods), activation (physical or chemical), and the template method (hard or soft templating), as summarized in Table 2. Recent advancements have also introduced techniques like laser-, microwave-, and solar-assisted carbonization. These methods influence the morphology, pore structure, and surface properties of the resulting carbon materials [81]. The choice of activation reagents and templating agents significantly affects porosity. Parameters such as temperature, reaction time, and precursor composition further determine the final material characteristics [82-83].

Carbonization

Pyrolysis

It is common practice to pyrolyze biomass to create porous carbon compounds and activate them to increase specific surface area and pore volume. Studies suggest that direct pyrolysis of biomass, without the activation phase, can produce high-performance carbon electrode materials [1]. Raymundo-Piñero et al. [84] reported developing a high surface area supercapacitor carbon

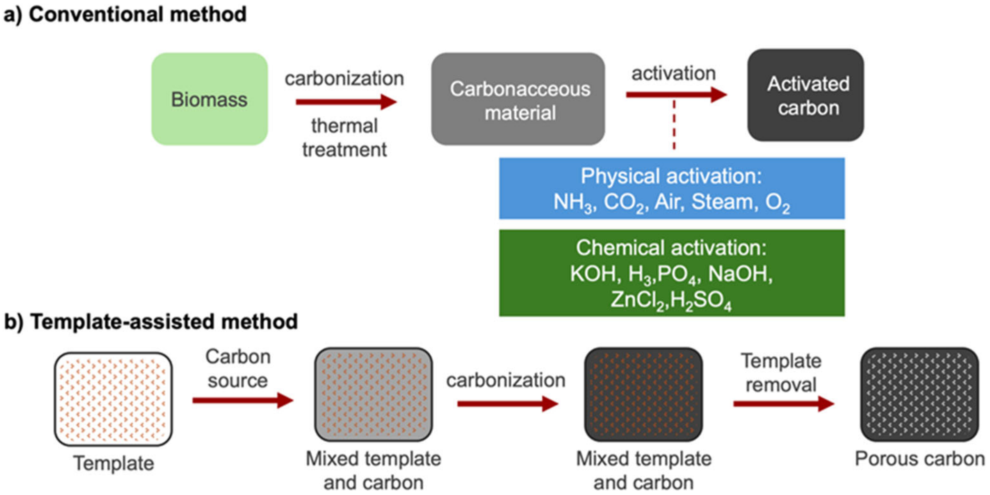

Fig 4. Schematic illustration of porous carbon synthesis routes via (a) conventional method from biomass via carbonization followed by physical or chemical activation, and (b) template-assisted method to yield porous carbon with controlled structure

Table 2. Synthesis methods for biomass-derived activated carbon

Synthesis method	Description	Types	Activating agents	Advantages	Disadvantages
Pyrolysis	Thermal decomposition method	Gas/physical assisted	Air, CO_2, steam	High yield, good electrical conductivity	Limited pore control, potential environmental impact
		Chemical assisted	KOH, NaOH, $ZnCl_2$, $CaCl_2$, $FeCl_3$, H_3PO_4		
		Self-activation	No activating agent		
Hydrothermal	Biomass in hot pressurized water, carbon-rich hydrochar	GO assisted	Water itself	Green method, precise porosity control	Energy-intensive, prolonged reaction times
Template method	Utilizes sacrificial or rigid templates to create controlled pore structures.	Soft template	Uses sacrificial templates to create pores	Precise pore control, versatility, customizable design	Complex setup, template removal challenges
		Hard template	Rigid templates create defined structures	Well-defined structure, customizable pores, replicable	Template reliance, template removal complexity

electrode material from discarded seaweeds that did not require activation. Biswal et al. [85] showed that activation is unnecessary in synthesizing high-specific surface area microporous carbon. The plant-leaf-derived carbon showed a high specific capacitance of 400 F g^{-1} in an aqueous 1 M H_2SO_4 electrolyte at a current density of 0.5 A g^{-1}. High concentrations of the good porogens Na, K, Ca, and Mg are present in all these biomass precursors.

Hydrothermal carbonization (HTC)

It is a feasible approach for transforming biomass into beneficial carbon compounds at relatively low temperatures (below 250 °C) in a water-based environment within a confined area. The characteristics of biochar (a product formed from hydrothermal carbonization), such as yield, shape, nanostructure, and surface functional groups, are significantly influenced by the temperature, pressure, time, and aqueous solution used during production [86]. The precursor undergoes decomposition into smaller monomers, which is then followed by dehydration, polymerization, and aromatization processes. The biochar's specific surface area and porosity experience an initial enhancement as the HTC temperature hits 200 °C. However, as the temperature rises, these properties are subsequently diminished due to a significant increase in aromatization. An additional activation process is typically required after subjecting biochar to high temperatures to increase its porosity, alter its surface chemistry, and improve its graphitization level [87].

Activation

Physical activation

A physical activation technique employs an oxygen-containing gas as an activator, such as water vapor, flue gas, or air, to react with atoms inside carbon compounds at high temperatures. Physical activation may be broken down into three stages: First, blocked adsorption media are removed; second, the holes created in the precursor material are extended; and last, new pores are generated by selective oxidation of the carbon precursor [88].

Chemical activation

The chemical activation technique refers to the high-temperature reaction of chemical activators (such as NaOH, KOH, and H_3PO_4) with raw materials. Carbon atom separation and gas escape caused by the reaction result in many pore structures in the activated carbon skeleton. The technique of chemical activation and the qualities of the result are heavily influenced by the type of activator used. The activator primarily dehydrates or erodes the raw materials before forming pores [89].

Template Method

Templates, such as hard and soft templates, have been recognized as effective for producing porous carbon materials with controllable porosity and organized structure [90]. Carbon precursors are combined with rigid templates such as SBA-15 silica, silica spheres, and metal oxides, and then subjected to polymerization and carbonization. Subsequently, templates are effectively removed, resulting in the formation of porous carbons. In addition, environmentally benign molten salts such as KCl, NaCl, and LiCl can be utilized as robust templates for synthesizing porous carbons [83]. However, this procedure requires a substantial quantity of water to rinse out salts during carbonization. Conversely, the soft-template method relies on the spontaneous arrangement of templates and precursors to produce porous carbon [86-87].

■ DESIGN STRATEGIES FOR HIGH-PERFORMANCE ELECTRODES

Biomass-derived porous carbon materials are popular electrode materials for supercapacitors due to their excellent characteristics. Researchers need to design and construct porous carbon materials rationally

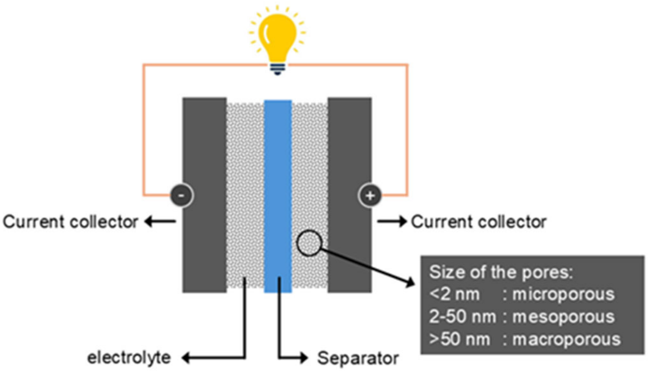

Fig 5. Illustration of porous carbon electrode-based supercapacitor

to maximize their potential in supercapacitors. Supercapacitors need to be optimized and regulated to achieve reliable performance in practical applications [91]. Fig. 5 depicts a porous carbon electrode-based supercapacitor, emphasizing four critical factors that influence the design and functional performance of such systems [92].

Hierarchical Porosity

The International Union of Pure and Applied Chemistry defines pores in materials as being categorized into three types based on their size: micropores (less than 2 nm), mesopores (2–50 nm), and macropores (more than 50 nm). Micropores and mesopores significantly enhance the material's specific surface area, hence exposing a greater number of active sites. Nevertheless, the distance between these two types of pores is considerable, impeding the efficient diffusion of ions or reactants [93-94]. Macropores can reduce the impedance of mass transfer. Thus, compared to porous materials with consistent pore sizes, hierarchical porous materials exhibit superior performance in real-world applications. The direct conversion of biomass molecules into carbonaceous materials is unlikely to produce porous structures, particularly hierarchical porous structures. Therefore, it is essential to pre-treat the biomass materials before carbonization [95].

Graphitization

Carbon's high conductivity minimizes internal resistance, enhances charge transfer, and stabilizes the structure, guaranteeing exceptional rate, power density, and cycling stability performance. Increased conductivity is typically associated with a significant level of graphitization. Nevertheless, this will lead to a limited surface area and an insufficiently formed pore structure. To optimize the electrochemical performance, one must consider the balance between specific surface area, pore structure and functional groups, and the level of graphitization [92,96].

Phase/Surface Modification

Recent studies reveal that the phase/surface properties of biomass-derived carbon materials, particularly doped heteroatoms, significantly influence their electrochemical performance due to the increased presence of defects and active sites and the modification of surface characteristics [97]. Nevertheless, achieving regulated heteroatom doping continues to be a difficult task in synthesizing materials derived from biomass. The level of heteroatom doping is frequently unpredictable, and the process by which it occurs remains unclear. Various varieties of doped N atoms, including pyrrolic N, pyridinic N, graphitic N, and oxidized N. However, further research is needed to determine the specific significance of each N type in boosting the performance of biomass-based materials. Furthermore, there is a pressing need for research on the correlation between carbonization parameters and the introduction of heteroatoms, to achieve adjustable heteroatom doping [98].

Composites

In addition to hierarchical pore structure, graphitization, and phase/surface modification, combining biomass-derived porous carbon materials with other carbon-based materials, such as graphene, CNTs, or carbon microtubes, as well as with pseudocapacitive materials like transition metal oxides/hydroxides, conducting polymers, or MXenes, as depicted in Fig. 6, can effectively enhance electrochemical performance [99-101]. A growing number of researchers have developed new composites, such as porous carbon/Ni_3S_2, porous carbon/MXene, porous carbon/NiCoS, porous carbon/NiP, and so on, which have demonstrated excellent performance in supercapacitor applications. For example, Sun et al. [102] created a hierarchical porous MXene/biomass-derived carbon fiber composite, facilitating electrolyte penetration and efficient ion diffusion. This composite was used as a self-supporting electrode for supercapacitors, achieving high volumetric capacitance and excellent cyclic stability. The impregnation of 2D materials was accomplished by incorporating porous carbon derived from wood through a freeze–thaw method combined with a LiCl salt-templating approach, resulting in a layered porous structure with enhanced

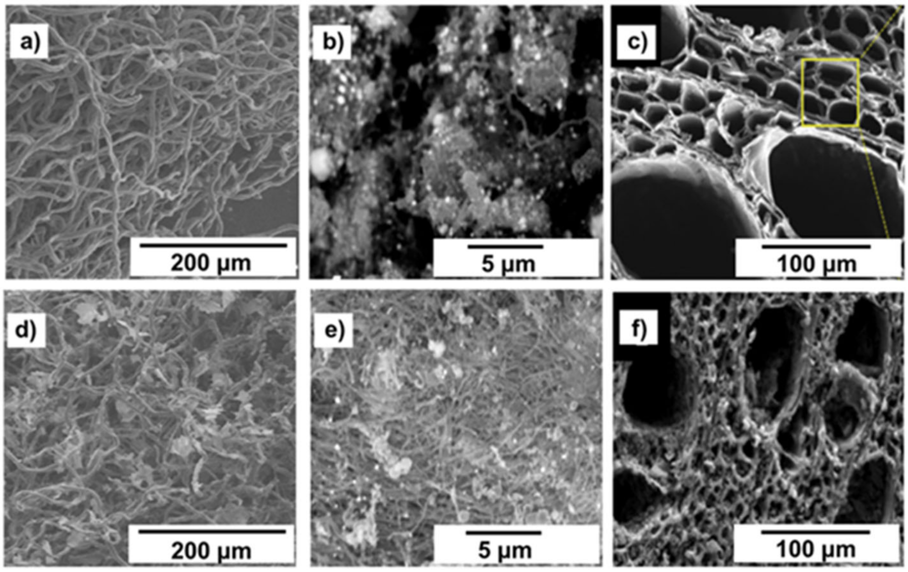

Fig 6. (a–c) Carbon precursors and (d–f) corresponding carbon-modified MXenes. (a, d) Carbon fiber integrated with $Ti_3C_2T_x$ [102]. (b, e) Nitrogen-doped CNT-$Ti_3C_2T_x$ using Co–melamine precursor [104]. (c, f) Carbon nanopores derived from wood integrated with MXene [103]. Reproduced with permission from Refs. [102-104]; Copyright 2021, 2023, and 2025 Elsevier

wettability and electrical conductivity [103]. A distinct tubular architecture, such as the MXene/N-doped CNT (MXene/N-CNT) hybrid, was successfully synthesized by Xiong and co-workers [104] via segmental pyrolysis of an MXene-Co-melamine composite precursor. This synthesis pathway yielded a well-defined hierarchical pore structure, characterized by an average BJH adsorption pore size of 11.5 nm, with a micro–mesoporous distribution comprising 1.94% micropores and 61.67% mesopores. The rational design of material features, including porosity, morphology, surface area, and dimensional control, is critical in enhancing electrochemical performance while maintaining structural integrity under mechanical deformation, demonstrating strong potential for supercapacitor applications.

■ MXenes

Since the 1950s, there has been extensive research on 2D nanolayer materials, such as graphene, because of their exceptional electrical, optical, mechanical, and thermal characteristics. Graphene has facilitated the emergence of novel 2D solid materials such as silicene, phosphorene, h-BN, and MoS_2 [105]. In 2011, researchers from Drexel University discovered MXenes, a novel form of 2D crystalline material. MXenes possess an atomically thin thickness while having theoretically unlimited lateral dimensions. Ternary carbides or nitrides (X = C or N) are produced through chemical etching of a MAX phase, resulting in the formation of 2D flakes with distinct characteristics. The discovery of titanium carbide (Ti_3C_2) marked the initial identification of MXenes [26,106]. Subsequently, the subject has been broadened by investigations on MXenes, aiming to elucidate their properties and applications. MXenes, which have diverse uses in energy storage, electromagnetic shielding, biology, and environmental fields, including water purification, are promising candidates for replacing existing materials [107].

Historically, MXenes have been derived from MAX phases, where M represents an element belonging to the early transition metals, whereas A represents an element found in groups 12 to 16. X, on the other hand, represents either carbon or nitrogen. The transformation of MXene from its original MAX phase requires the targeted elimination of A layers as demonstrated in Fig. 7. Prospective candidate lists can be derived from groups ranging from 12 to 16. Among them, aluminium (Al) has

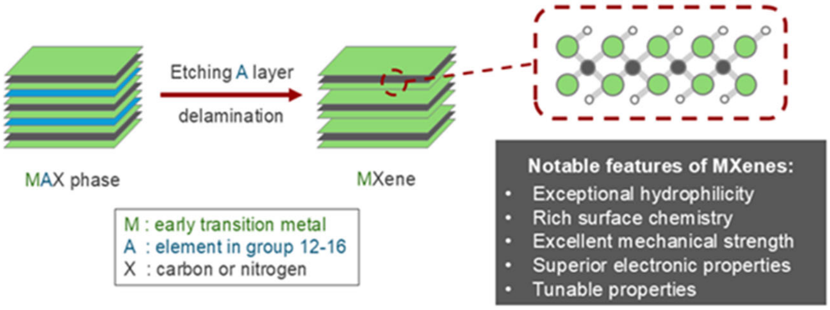

Fig 7. A schematic synthesis process, and key features of MXenes derived from MAX phases

emerged as a notable and extensively evaluated A-layer in MAX phases, including Ti_2AlC, Ti_3AlC_2, Ta_4AlC_3, and others. Consequently, numerous methods have shown the step-by-step elimination of Al layers using acid etching. The general formula for MXenes is $M_{n+1}X_nT_x$, where M represents an early transition metal, X represents carbon and/or nitrogen, T_x represents surface terminations, and n ranges from 1 to 4 [108].

MXene materials possess a distinct blend of characteristics, including a large surface area, exceptional electrical conductivity, pseudocapacitive behavior, flexibility, and compatibility with other materials that render them an up-and-coming contender for enhancing the performance of supercapacitors. This, in turn, facilitates progress in energy storage technology by augmenting energy density, power density, and cycling stability [109]. Although the charge storage mechanism of MXenes in different electrolyte systems is not entirely understood, it has been observed that MXenes display an electric double layer capacitive behavior in aqueous electrolytes. This behavior is attributed to the formation of solvated cations in the interlayer spacing within MXene sheets. MXenes primarily have a pseudocapacitive activity in non-aqueous electrolytes, characterized by charge transfer redox processes between surface termination groups and cations. This process is called intercalation pseudocapacitance, which is caused by the creation of donor bands from desolvated cations [110].

Despite its promising potential in energy storage, MXene nanosheets tend to stack and aggregate during electrode manufacturing due to the strong van der Waals interaction between adjacent nanosheets, a common characteristic of other 2D nanomaterials. As a result, the MXene film has a significantly smaller specific surface area than graphene, even less than one-tenth. This limitation hinders the transport of ions within the nanosheets and restricts the number of contact sites that may be accessed. Furthermore, the self-reliant MXene film utilized as flexible electrodes lacks sufficient mechanical strength to endure prolonged bending cycles. Consequently, investigating MXene-based electrical components with high capacitance and excellent mechanical strength remains difficult [88].

In addition to structural and mechanical challenges, $Ti_3C_2T_x$ and related MXenes are highly prone to oxidation, especially in aqueous environments or upon air exposure. This oxidation, often leading to the formation of TiO_2, degrades electrical conductivity and compromises long-term performance. Factors such as ambient moisture, oxygen, flake size, surface defects, and light exposure can accelerate this degradation. Huang et al. systematically investigated the degradation behavior of Ti-based MXenes (Ti_2CT_x, $Ti_3C_2T_x$, and Ti_3CNT_x) under different oxidative environments and identified various gaseous byproducts, including methane, carbon oxides, and C_2 hydrocarbons, highlighting the complex chemical pathways involved and the need for more robust stabilization strategies [111]. Various approaches have been explored to address this issue, including thermal treatment in inert atmospheres, antioxidant additives, protective surface coatings, and encapsulation methods to inhibit oxygen and water diffusion. One notable example is the work of Qian et al. [112], who demonstrated that depositing a nanoscale copper layer onto MXene films (MXene@Cu) significantly enhanced oxidation resistance, with conductivity retention of 72% after 30 d compared to only 44.3% in pristine films. Recent efforts also focus on surface termination engineering, where –Cl terminations have shown greater oxidative stability than conventional –O or –F groups, and emerging terminations like –Br, –S, or –Te are being studied for similar benefits. Additionally, ionic liquid storage, hybrid composite formation, and chemical surface modification offer promising avenues to extend MXene stability. Continued research in these areas is essential for enabling the long-term deployment of MXenes in practical energy storage and electronic applications [113].

As research advances, a growing interest has emerged in diversifying MXene compositions as reflected in Fig. 8. Depending on the transition metal involved, MXenes can be broadly categorized into Ti-based and non-Ti-based types, with non-Ti metals including Sc, V, Cr, Y, Zr, Nb, Mo, Hf, Ta, W, and Lu. Approximately 70% of MXene research has focused on Ti-based systems, while the remaining 30% covers other transition metals. This disparity is primarily due to the challenging and less-developed synthesis methods for non-Ti MXenes. Many of these materials have yet to be experimentally synthesized and exist only in theoretical or computational studies. Nonetheless, they are predicted to exhibit outstanding properties and significant application potential, often surpassing conventional Ti-based MXenes [108].

Synthesis Methods

Various techniques exist to produce MXenes, which can be broadly classified into two categories: Firstly, the conversion of MAX phase to MXene occurs top-down. At the same time, the bottom-up approach involves the reaction of individual precursor components [114].

Top-down synthesis approach

The predominant method employed to produce 2D MXene is the top-down approach, which involves a series of steps such as precursor synthesis, etching, and exfoliation. During these methods, the MAX phase transforms a 2D MXene [109]. The synthesis process involves creating layered MXene precursors, which have a crystal structure derived from either MAX ($M_{n+1}AX_n$, where "A" represents group 11–16 atoms such as Al, Si, Ga) or non-MAX phase layered materials with multiple "A" atomic layers (e.g., $M_{n+1}AX_n$) or carbide layers of A-elements (e.g., MA_3X_{n+2}). Next, the "A" atomic layers are removed through etching, resulting in the exfoliation of the precursors and the formation of MXene multilayers with weak bonding. During the "A" atomic layer etching process, the M-A bonds, which are weaker compared to M-X bonds, are broken. This leads to the formation of M metallic surfaces with fewer neighboring atoms. These surfaces quickly become saturated again by reacting with the T_x species in the etchant. Next, the multilayer MXene sheets are separated to produce MXene sheets with only one to a few layers [112].

Different etchants are employed in MXene synthesis to selectively remove the A layers from MAX phases, determining the quality, surface chemistry, and structural integrity of the resulting MXenes. The effectiveness of this process depends on the type of etchant used and the nature of the A element and M–A bond strength [109]. Among the widely used approaches Etching process was divided into two pathways, the first one uses the acidic solution like HF, LiF, NaF, KF which assisted by HCl and

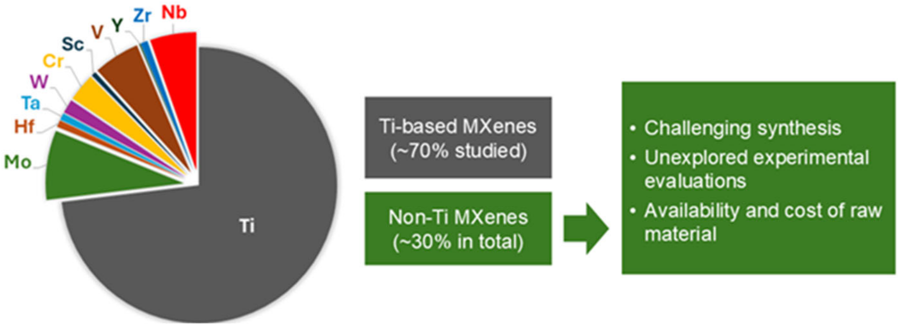

Fig 8. A comparative overview of research trends in Ti-based and non-Ti MXenes

LiCl resulted high purity (> 90%) of MXene with uniform structure [109,115] and increasing the yield until 38% of product with high conductivity performance (~21,000 S/cm) [114]. The last pathway is the etching mechanism led by molten salt methods, which provides a fluoride-free alternative for selective elimination of Al from the MAX phase substrate [116]. These pathways usually use $CuCl_2$, NaCl, and KCl [111-113,117] to produce good purity of MXene and control the surface functionalization. Among the widely used approaches, delamination is a critical step in the top-down synthesis of MXenes, as it enables the separation of multilayered structures into mono- or few-layered flakes with enhanced surface area and functionality. For instance, Zhang et al. [118] obtained free-standing $Ti_3C_2T_x$ paper by sonicating exfoliated products under argon, followed by centrifugation and vacuum-assisted filtration, enabling quantifiable delamination efficiency [119-120].

Various delaminating agents have been employed to weaken interlayer interactions and facilitate exfoliation. Among these, polar organic molecules such as dimethyl sulfoxide (DMSO) and isopropanol are widely used because they can intercalate between MXene layers and assist in their separation, especially when combined with sonication. This process typically yields stable colloidal suspensions of delaminated MXenes, which can be further processed into films or membranes. Jothibas et al. [121] reported effective delamination using DMSO treatment followed by prolonged ultrasonication, resulting in D-MX with excellent cyclability and 86.21% capacitance retention after 1000 cycles, highlighting its promise as an electrode material.

The choice of delaminating agent significantly affects the final product's thickness, flake size, crystallinity, and surface chemistry. For example, higher concentrations of LiF during synthesis can facilitate delamination even without sonication, resulting in larger monolayer flakes. In contrast, lower LiF concentrations with sonication tend to produce smaller multilayer flakes due to mechanical breakdown. Similarly, *in situ* HF etching using NH_4HF_2 promotes spontaneous delamination into few-layer MXene sheets, with the ammonium ion itself acting as the delaminating agent. Thus, carefully selecting delaminating conditions is essential for tailoring MXene morphology for specific applications [122].

Bottom-up synthesis approach

The synthesis of MXenes using the bottom-up method is currently in a developmental phase. Various bottom-up synthesis techniques, such as chemical vapor deposition (CVD), template approach, and plasma-enhanced pulsed laser deposition, have recently emerged. Further exploration is required to investigate the synthesis of various monolayered MXene phases with improved crystallinity and uniformity [114].

CVD Route

In the CVD process, the substances on the surface are absorbed, resulting in a reduction in surface diffusion. Xu et al. showcased this technique in creating films by employing a copper/transition metal bilayer metal foil. The stack underwent a thermal treatment at a temperature of 108.5 °C in a hydrogen environment to facilitate the formation of molybdenum carbide crystals. Methane was used as the source gas for this process. The uppermost liquid layer of copper played a crucial role in crystallization. In addition, copper acted as a catalyst for the synthesis of carbon from methane and facilitated the migration of melodeum atoms into liquid copper, creating extremely thin layers. Despite initial assumptions, the thinnest layer of MO_2C was not composed of a single MXene sheet but consisted of six MO_2C layers [123].

Other Fabrication Routes

Implementing the template approach in the fabrication of 2D materials aims to attain high yields, as the CVD process provides low results. This technique utilizes 2D nanosheets of transition metal oxides, which undergo carbonization or transform into nitrides. The selection of transition metal oxide dictates the arrangement of transition metal carbides or nitrides. Joshi et al. [124] employed this method to produce 2D hexagonal MoN nanosheets. They achieved this by subjecting 2D (MoO_3) nanosheets to a temperature of 800 °C in the presence of ammonia, causing them to transform into MoN nanosheets. The synthesis of 2D MoN nanosheets led to the development of a structure resembling layers [123]. In addition, Zhang et al. [125], suggested a method called plasma-enhanced pulsed laser deposition to create extremely thin Mo_2C films. This methodology combines the techniques of CVD and pulsed laser deposition. The films were synthesized by subjecting the sapphire substrate to a temperature of 700 °C while utilizing methane as a carbon source. However, films created using this method were discovered to have poor crystalline quality and notable stacking flaws [126].

■ MXene-BASED COMPOSITES

In recent years, fabricating composites has been an appealing approach for creating durable and adaptable materials. MXenes, with their 2D morphology, layered structures, and excellent flexibility, are highly regarded as exceptional options for creating multifunctional composites. The presence of –T functional groups on the surface of MXenes introduces negative charges, facilitating the combination of MXenes with positively charged materials due to the ability of –OH and –F groups to form hydrogen bonds [127-128]. This has led to a significant increase in research on composites based on MXenes. Thus far, many innovative composites have been created by combining MXenes with other substances such as polymers, metal oxides, and carbon nanotubes [129].

MXene–Polymer Composites

Polymers possess the benefits of a malleable structure, economical production, and minimal toxicity, resulting in extensive utilization. The combination of MXene and polymer compound can enhance the performance of materials in various aspects, including thermal stability, mechanical characteristics, electrical conductivity, and more. Single-layer MXenes have higher surface hydrophilicity and improved compatibility with polymers compared to multi-layered MXenes. Polymer/MXene compounds can be synthesized using *in situ* polymerization and *ex-situ* mixing techniques. The *ex-situ* mixing method involves the preparation of the polymer as a sheet, considering its features. This facilitates the formation of a composite material on a filter membrane. Nevertheless, the interaction between the composites is restricted, thus implementing a rolling motion might be seen to improve the connection between their surfaces. In addition, the compounding procedure may result in poor distribution due to the lengthy polymer chain. Enhanced uniformity can be achieved by combining with a polymer of lower molecular weight or chain length. The *in situ* polymerization technique achieves a homogeneous polymer dispersion onto the MXene surface. The drawbacks of this approach include the prerequisite for the monomer to possess adequate polymerization energy and the necessity for the process not to compromise the characteristics of the MXene material [130].

MXene–Metal Oxide/Sulfide Composites

MXene-metal oxides and sulfides have a significant potential to increase the energy storage capacity of materials based on MXene. MXenes can also prevent metal oxide and sulfide formations from collapsing structurally. Furthermore, the insertion may limit the MXene layer's restacking. As a result, various metal sulfides and oxides have been employed to create composites based on MXene. The notable materials are TiO_2, SnO_2, MnO_2, MoO_3, Cu_2O, Sb_2O_3, Fe_2O_3, Co_3O_4, $NiCo_2O_4$, Nb_2O_5, ZnO, MoS_2, ZnS, and SnS [27,111].

MXene–Oxide Composites

Researchers are urged to create a hybrid mixture of MXene and metal oxides to improve the performance of supercapacitors. This is because the electrical conductivity in binary oxides is twice as high as that of single oxides. Therefore, zinc-based binary metal oxides exhibit favorable conductivity, reduced expense, and lower toxicity, making them superior candidates for high-capacitance asymmetric supercapacitors. Thus far, there have been four published methods for synthesizing MXene/Metal oxide composites, including *ex-situ* mixing, self-oxidation mixing, one-step *in situ* growth, and multistep *in situ* conversion. Varying synthetic processes yield distinct product architectures and performance outcomes. The selection of the most suitable approach for increasing the number of cavities available for depositing metals or metal compounds depends on the specific material being targeted and its precursor substances, to obtain a layered structure [34,131].

MXene–Sulfide Composites

Extensive research has been conducted due to the rapid ionic conductivity shown by layered metal sulfides. MoS_2, a material with a disulfide structure, has garnered significant attention due to its potential. As a result, numerous investigations have been conducted on MoS_2/MXene composites. Theoretical studies showed indirect band-gap semiconductor features in certain MXene/MoS_2 composites. The typical approach for producing composites of MXene and metal sulfide involves employing an *in situ* hydrothermal process. ZnS and MoS_2 can be synthesized from their precursor materials using a one-step hydrothermal technique. These sulfides can then be applied to the surface of MXene. However, many sulfides, such as SnS, require ongoing heat treatment to be derived from their component elements [132].

MXene-Metal Composites

Metals possess exceptional electrical conductivity and catalytic capabilities, making them valuable components for enhancing the characteristics of materials. The synthesis of MXene metal composites mainly involves the in-situ reduction process. The surface groups of MXene possess a negative charge, which facilitates the dispersion of metal ions for compositing. Additionally, the surface hydroxyl (–OH) groups can react with metal ions, forming metal-oxygen (M–O) groups. This interaction leads to a more uniform distribution of the metal ions on the surface. The *ex-situ* mixing approach is less complex than the in-situ method. The MXene solution is evaporated on a metal substrate to yield a composite. Nevertheless, the evenness of the dispersion achieved by this method is not comparable to that of the *in situ* composite method. Furthermore, M/MXene compounds can be synthesized using a multistep conversion technique, in addition to the two ways mentioned earlier. Due to the difficulty of converting specific metal ions into pure metals in liquid form, M/MXene composites can be created by synthesizing their oxides or sulfides and reducing them, often under a hydrogen atmosphere. Overall, MXene/metal composites have demonstrated exceptional electrical conductivity and catalytic activity, making them valuable components for enhancing the characteristics of materials [22].

MXene–Carbon Composites

Extensive studies have focused on integrating MXene with carbon materials in supercapacitors due to the exceptional combination of features that these composites provide. MXenes contribute exceptional electrical conductivity, enhancing charge transport and reducing internal resistance, while carbon materials provide high surface area and structural stability, both of which are critical for achieving high capacitance and long-term cycling durability. The synergistic interaction between MXene and carbon phases results in improved energy and power densities compared to their individual components. Through ongoing testing and optimization, MXene–carbon composites have emerged as promising candidates for high-performance supercapacitor electrodes, offering a significant advancement in energy storage technologies [133-135].

Other MXene-Based Composites

Apart from metals, carbon-based materials, metal oxides, metal sulfides, and polymers, MXene has been combined with various other materials, including metal-organic frameworks, metal organics, metal hydrides, sulfur, glass fibers, and graphene-like carbon nitride (g-C_3N_4), in rechargeable battery systems [135]. Heteroatom doping is a practical approach to enhance the specific capacitance of MXene. This method facilitates the strong intercalation of heteroatoms into the MXene layers, preventing aggregation and creating particular spacing. These combinations have demonstrated exceptional electrical performance [136].

■ INTEGRATION OF MXene INTO BIOMASS BASED SUPERCAPACITORS

The prevailing electrode materials predominantly comprise carbon nanotubes, graphene, other carbon-based materials, and certain pseudocapacitive active materials such as Co_3O_4, NiO, and PPy. However, other obstacles persist, including the need for carbon materials that exhibit excellent conductivity and stability while maintaining low capacitance and pseudocapacitive materials that possess high capacitance but suffer from inadequate conductivity and stability. Thus, despite their respective advantages, these materials do not adequately achieve a synergistic combination of conductivity, stability, and capacitance. The existing limitations in electrode performance underscore the need to investigate composite materials that may effectively integrate the advantageous characteristics of many materials, thereby mitigating the inherent limitations of each component [2].

Synthesis and Fabrication of MXene/Carbon Composites

MXene/carbon composites are synthesized using various methods, each imparting distinct properties to the resulting material. One widely used approach is ball milling, a mechanical procedure involving the simultaneous grinding of MXene and carbon materials. Researchers have employed this technique to achieve a precise and consistent dispersion of MXene within the carbon matrix. The method is valued for its simplicity and cost-effectiveness. In contrast, self-assembly relies on the autonomous arrangement of MXene and carbon nanoparticles. This process has been shown to hinder the re-stacking of MXene layers and enhance composite porosity, thereby improving electrochemical performance [31-32].

Another common technique is spray drying, where a liquid mixture of MXene and carbon materials is atomized into small droplets and introduced into a high-temperature chamber, rapidly forming a dry powder. This method enables effective control over particle size and shape, which is essential for optimizing the electrochemical properties of the composite. Vacuum-assisted filtration, meanwhile, facilitates the formation of layered or stacked MXene–carbon structures. It is particularly effective for producing thin and flexible composite films, making it ideal for high-performance supercapacitor applications [23,129].

More advanced strategies include in-situ growth, where carbon is chemically deposited onto MXene surfaces [137] This method is employed to tailor the composite's physical and chemical characteristics, enhancing its conductivity and structural stability. Finally, electrospinning produces fibrous composites by spraying a solution containing MXene and carbon-based components. The resulting fibers offer a large surface area and controlled porosity, which are highly advantageous for ion transport and charge storage in supercapacitors. Together, these diverse synthesis approaches provide multiple routes for tailoring the structural and electrochemical features of MXene–carbon composites, reinforcing their promise for next-generation energy storage devices [129].

Advances in MXene/Carbon Composites as Supercapacitor Electrodes

MXene/carbon composites have emerged as an up-and-coming class of hybrid materials for energy storage, offering a combination of the exceptional electrical conductivity and surface functionality of MXenes with the mechanical strength, stability, and porous structure of various carbon forms. These composites effectively address limitations such as MXene restacking, limited electrolyte access, and low cyclic stability, often hindering standalone electrode materials. To provide representative insight into the structural and electrochemical characteristics of MXene/carbon composites, Fig. 9 presents typical characterization data for MXene-coated mesoporous carbon, highlighting architectures designed to facilitate ion transport, enhance electrical conductivity, and improve both volumetric and areal capacitance [29].

Several studies have demonstrated innovative approaches to tuning MXene/carbon interfaces. Yan et al. [138] expanded the interlayer spacing of MXenes using reduced graphene oxide (rGO), enhancing ionic diffusion and access to electroactive sites, thereby improving volumetric capacitance and long-term retention. In another example, Wang et al. [139] fabricated flexible MXene/CNT yarn electrodes, which, when combined with RuO_2, delivered stable capacitance even after 1000 mechanical bending cycles, indicating potential in wearable energy storage systems. Yu et al. [140] advanced a binder-free electrode fabrication method using $Ti_3C_2T_x$ MXene as a multifunctional binder for activated carbon, significantly boosting capacitance and

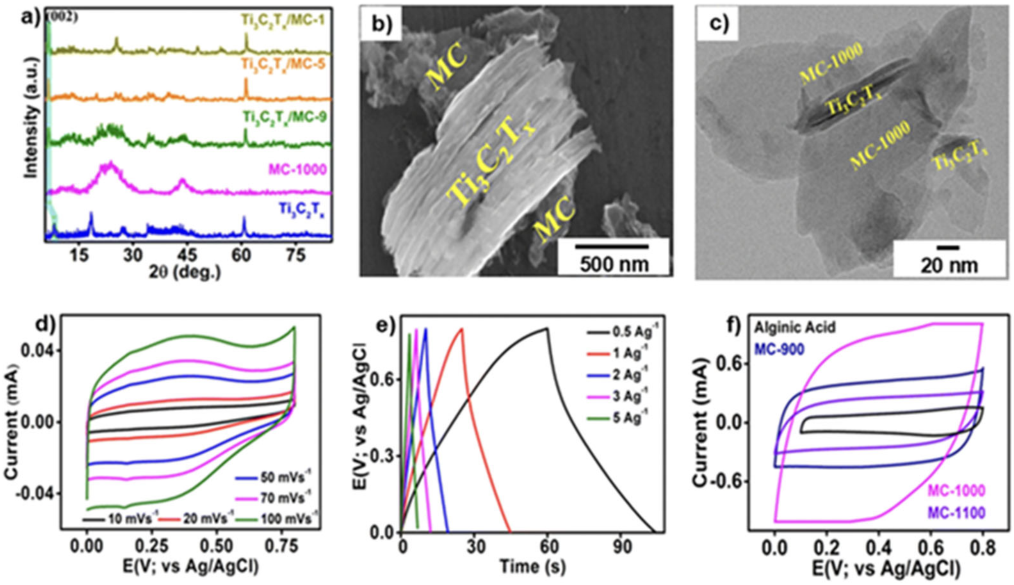

Fig 9. (a) XRD spectra of carbon mesopores and MXene, (b) SEM images, (c) TEM images, (d) CV curves at various scan rates, (e) GCD curves at various current densities, and (f) comparative CV profiles of alginic acid and carbon mesoporous material. Reproduced with permission from [30], Copyright 2025 Elsevier

rate performance while avoiding insulating polymeric additives. Similarly, Levitt et al. [141] produced MXene/carbon nanofiber composites by electrospinning MXene with PAN and subsequent carbonization, resulting in a notable increase in areal capacitance compared to pure PAN nanofibers.

Further progress includes Sun et al. [142] development of a three-dimensional neuron-like MXene/N-doped carbon foam (MXene/NCF), which provided interconnected ion channels and enhanced conductivity, leading to improved rate capability and volumetric performance. Li et al. [143] addressed MXene restacking by directly growing multi-walled CNTs on MXene sheets, improving structural integrity and interfacial contact. Liang et al. [144] demonstrated an asymmetric supercapacitor design combining MXene–MCNT as the negative electrode and PPy-coated MCNT as the positive electrode, enhanced by the use of chelating dispersants and hydrophilic binders that reduced resistance and boosted capacitance. Yang et al. [145] engineered a hybrid composite of MXene, CNTs, and porous carbon via vacuum filtration, resulting in a continuous conductive network with high area-specific capacitance and efficient charge transport. These collective advancements, as summarized in Table 3, affirm the adaptability of MXene/carbon architectures and their vital role in advancing flexible, high-performance supercapacitor technologies.

Despite these advancements, one of the key limitations in MXene/carbon composite development lies in the interfacial compatibility between the two materials. The surface of MXenes, enriched with –OH, –F, and =O terminations from chemical etching, is inherently hydrophilic and chemically reactive. In contrast, carbon materials, unless pre-treated or functionalized, are typically hydrophobic and chemically inert. This disparity results in weak interfacial bonding and poor MXene adhesion on carbon substrates. As such, new approaches that promote strong interfacial coupling while preserving the desirable properties of both components are critical for advancing the long-term performance and stability of MXene/carbon-based energy storage systems [143].

Advancements and Challenges in $Ti_3C_2T_x$ MXene-Coated Carbon Fibers

Recently, there have been notable advancements in applying $Ti_3C_2T_x$ MXene as a coating on carbon fiber.

Table 3. MXene carbon composites for supercapacitor electrode

Mien hybrid	Synthesis method	Electrolyte	Highest scan rate (mVs^{-1})	Capacitance (Testing conditions)	Rate capability (Testing conditions)
N-Ti_3C_2 MXene [146]	Hydrothermal reaction	KOH	5.00	156.00 F g^{-1} (2 mVs^{-1})	-
MXene/CNT yarns [139]	Biscrolling method	H_2SO_4	5.00	523.00 F g^{-1} (2 mA cm^{-2})	-
AC/$Ti_3C_2T_x$ MXene film [140]	Single-step fabrication	Et_4NBF_4/AN	4000.00	126.00 Fg^{-1} (0.1 Ag^{-1})	57.9% (100 A g^{-1})
$Ti_3C_2T_x$/CNT/PC [141]	Electrospinning	H_2SO_4	1.00	239.00 mF cm^{-2} (10 mVs^{-1})	57.9% (100 A g^{-1})
$Ti_3C_2T_x$/CNT/PC [145]	Vacuum filtration	PVA-KOH	1.00	212.00 mF cm^{-2} (0.1 mA s^{-1})	65.5% (10 mA cm^{-2})
MWCNTs-MXene/CC [143]	*In situ* growth	PVA-H_2SO_4	100.00	114.58 mF cm^{-2} (1 mA cm^{-2})	100.0% (5 mA cm^{-2})
$Ti_3C_2T_x$/rGO composite aerogel [147]	Freeze drying & laser cutting	PVA-H_2SO_4	100.00	34.60 mF/cm^2 (1 mVs^{-1})	~26.6% (100 mVs^{-1})

These include $Ti_3C_2T_x$/CC, MXene-coated activated carbon cloth, and MXene-coated silk-derived carbon cloth. Nevertheless, there persist specific issues. Initially, the impedance to charge transfer increases because of the feeble binding strength between MXene and carbon fiber. Furthermore, the MXene material will detach from the carbon fiber, reducing conductivity when subjected to twisting and bending. Ultimately, the electrochemical performance experienced a notable decline throughout the cycling process, indicating inadequate stability. Thus, creating an MXene nanosheet/substrate heterostructure with a porous configuration can augment adhesive strength and provide reliable, effective ion/electron transmission pathways. This approach offers a practicality for using electrode materials with large storage capacity in supercapacitors. However, the design of heterostructure materials still poses a difficulty [148].

Structural Optimization of MXene

Prior research on the advancement of MXene-based functional fibers has indicated that the presence of –F, –O, and –OH groups on MXene surfaces allows for their attachment onto various natural and synthetic substrates that possess hydroxyl or amine functional groups on their surfaces. This attachment is facilitated through electrostatic interactions, hydrogen bonding, and robust coordination bonds with titanium [112-114]. To address the issue of chemical incompatibility between carbon fibers and MXenes and to increase their specific capacitance, Dharmasiri et al. [134] carefully coated carbon fibers with MXene by modifying the surface of carbon fibers using several diazonium salts, each containing unique functional groups. Moreover, incorporating poly(*o*-phenylenediamine), a conductive polymer containing amine functional groups along its polymer chains, was essential for forming stable chemical bonds with MXene films. The intrinsic electrical conductivity of carbon fibers greatly aided the electrochemical functionalization of the carbon fibers' surface while maintaining their mechanical qualities intact. The enduring stability of the carbon fiber electrode interphase was achieved by covalently bonding diazonium salts and the polymer to the carbon fiber surface, followed by the adhesion of the MXene layer by chemical interactions.

■ FUTURE PERSPECTIVES AND CHALLENGES

In conclusion, the primary focus is on developing cutting-edge energy storage technologies that demonstrate outstanding performance, environmental friendliness, and cost-effectiveness. Although there have been notable advancements in biomass-based supercapacitor composites in recent years, some challenging obstacles still need to be overcome to enable their extensive use in different industries as outlined in Fig. 10 [12,43,149].

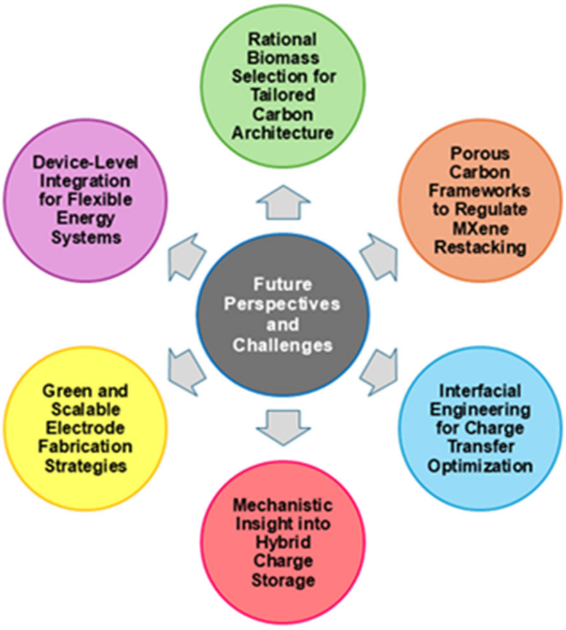

Fig 10. Schematic overview of future directions and key challenges in the development of MXene/carbon-based supercapacitors

Rational Biomass Selection for Tailored Carbon Architecture

One of the core challenges is selecting appropriate biomass precursors that can yield carbon materials with desired structural and electrochemical features. Most raw biomass is structurally complex and contains impurities, making it unsuitable for direct use. Developing low-cost, eco-friendly preprocessing strategies to enhance graphitization, surface functionality, and pore control remains essential for tailoring carbon materials for energy applications [12,78,150].

Porous Carbon Frameworks to Regulate MXene Restacking

Although MXenes offer excellent conductivity and capacitance, they are prone to restacking, which limits ion transport. Designing porous carbon frameworks that physically prevent this restacking can enhance the accessibility of active sites and improve electrochemical performance. Biomass-derived porous carbon, with its tunable pore distribution, offers a potential solution, but achieving consistent, controlled porosity across scales remains a key challenge [23,150].

Interfacial Engineering for Charge Transfer Optimization

Efficient charge transport across the electrode-electrolyte interface is critical to supercapacitor performance. The compatibility of biomass-based carbon with MXenes and electrolytes must be improved through surface chemistry control and interface engineering. *In situ* monitoring techniques that track charge dynamics and structural changes during operation can provide valuable insights for optimizing interfacial interactions [151].

Mechanistic Insight into Hybrid Charge Storage

Understanding the fundamental mechanisms of charge storage in hybrid systems that combine EDLC and pseudocapacitance is still limited. In particular, the complex interactions between MXene layers, functionalized biomass-derived carbon, and electrolyte ions require deeper investigation at the atomic and molecular levels. Such insight will be key to enhancing capacity, cycling stability, and rate performance [20,23].

Green and Scalable Electrode Fabrication Strategies

Current fabrication methods for biomass-derived electrodes often involve high temperatures, acid/alkali treatments, and energy-intensive processes. Transition toward greener and scalable methods that minimize environmental impact while maintaining material performance is vital. This includes exploring solvent-free synthesis, low-temperature carbonization, and renewable energy-driven fabrication processes [9].

Device-Level Integration for Flexible Energy Systems

To meet the demands of future wearable and portable devices, supercapacitor systems must be lightweight, flexible, and seamlessly integrable. Integrating MXene/carbon composites into such device architectures requires advances in flexible substrate compatibility, mechanical stability, and energy density optimization. Furthermore, a multifunctional design that combines energy storage with sensing or structural functions can broaden the scope of application of these materials [12,43].

CONCLUSION

This review presents a comprehensive overview of biomass-derived carbon materials and their integration with MXenes for supercapacitor applications. Beginning with the fundamental working principles and classifications of supercapacitors, the review emphasizes the significance of biomass as a sustainable carbon precursor. Various biomass sources have been examined to combine with MXene for supercapacitor applications with a focus on their primary components such as cellulose, lignin, and hemicellulose, along with several conversion techniques. While significant progress has been made, the relationship between biomass composition, processing methods, and electrochemical performance requires further investigation. Additionally, advanced design strategies such as heteroatom doping, surface functionalization, hierarchical structuring, and the development of hybrid composites can further enhance their charge storage capabilities. MXenes, with their high conductivity, tunable surface terminations, and layered structures, offer notable advantages when combined with biomass-derived carbons. This integration improves ion transport, electrical conductivity, and structural stability, effectively addressing the limitations of pure carbon materials. By utilizing the sustainability of biomass alongside the electrochemical strengths of MXenes, these hybrid electrodes show strong potential applications as supercapacitor. To fully realize their potential, future research should emphasize scalable synthesis, improved interfaces, cost-effective production, and industrial scale-up to achieve practical and sustainable applications

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Syeda Sheeza Nadeem contributed to the conceptualization, analysis, writing, and revision of the manuscript. Afiten Rahmin Sanjaya assisted in the writing and provided supportive input during manuscript preparation. Munawar Khalil contributed to the supervision, analysis, and critical review of the manuscript. Tribidasari Anggraningrum Ivandini was responsible for project supervision, funding acquisition, and final review of the manuscript.

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