

Fabrication of 3D Flexible Electrode Derived from Biomass Material for Hybrid Supercapacitor via Electrospinning



By

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**Fabrication of 3D Flexible Electrode Derived from
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A Thesis Presented to

COMSATS University Islamabad, Lahore Campus

In partial fulfillment

of the requirement for the degree of

MS (Physics)

By

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January 2024

Dedication

To

My Parents, Teachers, Brother, sisters, Friends and those

Persons who respect the Human beings and do not make tease and loss to others

Gulnaz

Muhammad Amin

Fabrication of 3D Flexible Electrode Derived from Biomass Material for Hybrid Supercapacitor via Electrospinning

A Post Graduate Thesis submitted to the Department of Physics as partial fulfillment of the requirement for the award of Degree of MS (Physics)

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Abstract

Balsa wood, a naturally occurring material that is renewable and environmentally friendly has undergone delignification protocol. Flexible electrodes play a pivotal role in the development of wearable electronics, enabling conformable and adaptable interfaces for comfortable user interactions and various biomedical applications. Fossil fuels, although once the cornerstone of global energy, now face increasing scrutiny due to their environmental impact, spurring efforts towards cleaner, renewable energy sources and technologies. In this work, nanofibers composites including reduce graphene oxide (rGO), polypyrrole (PPy), and polyvinyl alcohol (PVA) as rGO/PPy are deposited on balsa wood template using an easy, low-cost, and sustainable approach which is the electrospinning technique. Nanofibers composites were characterized by Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), Raman spectroscopy and electrochemical measurements CV, GCD, EIS done by Corrtest workstation (China). The highest specific capacitance is 52mF/g was obtained at 0.05mA current density. The redox peaks in CV show its hybrid nature so prepared flexible electrode which is derived from balsa wood is suitable and reliable for hybrid supercapacitors.

Keywords: Nanofibers, electrospinning, polypyrrole, reduce graphene oxide, Hybrid supercapacitor, balsa wood

List of Abbreviations

Terms	Abbreviations
Super capacitor	SC
Cyclic voltammetry	CV
Electric double layer capacitors	EDLCs
Electrochemical Impedance Spectroscopy	EIS
Energy density	Ed
Galvanostatic Charge Discharge	GCD
Graphene Oxide	GO
Reduce graphene oxide	rGO
Scanning Electron Microscopy	SEM
Specific capacitance	Csp
X-ray Diffraction	XRD
Delignified balsa wood	DBW
Polypyrrole	Ppy
Polyvinyl alcohol	PVA
Nanofibers	NFs
Energy-dispersive X-ray spectroscopy	EDS

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Chapter 1 Introduction

1.1 Background

Environmental concerns are one reason for the rising popularity of renewable energy. In addition to supplying the need for power, renewable energy sources including wind, solar, hybrid supercapacitors, geothermal, and wave energy also contribute to reducing global warming. The greatest challenge of the century is finding sustainable, dependable, and clean energy due to the fast-evolving lifestyle, increasing fuel shortages, and growing environmental concerns. The energy sources of the future must be more flexible, dependable, and greener while also being more efficient and effective. Growing energy and environmental problems are alarming human society. Worldwide research has concentrated on creating prototype devices for energy conversion and storage as well as sustainable energy storage materials [1][2][3].

Supercapacitors, also known as electrochemical capacitors and ultracapacitors, have been the subject of extensive research in recent decades due to their exceptional reversibility, long cycle life, and high-power capability [3][4]. Supercapacitors can be broadly categorized into two types based on how they operate: (1) Electrical double-layer capacitors (EDLCs) such as carbon-based supercapacitors where capacitance results from the charge separation at the electrode/electrolyte interface and (2) pseudocapacitors, where capacitance results from reversible faradic reactions that take place at the electrode surface [5][6].

The Ragone plot, which displays the specific energy and specific power of typical energy storage and conversion devices, is depicted in Figure 1.1 [7]. Conventional

capacitors are found to have a higher power density than fuel cells and batteries. Additionally, supercapacitors have a higher energy density than regular capacitors. The difference between conventional supercapacitors and supercapacitors is that the former store charge on low plan section, while the final charge store in an electric double layer created by ions of electrolyte and electrode at the interface.

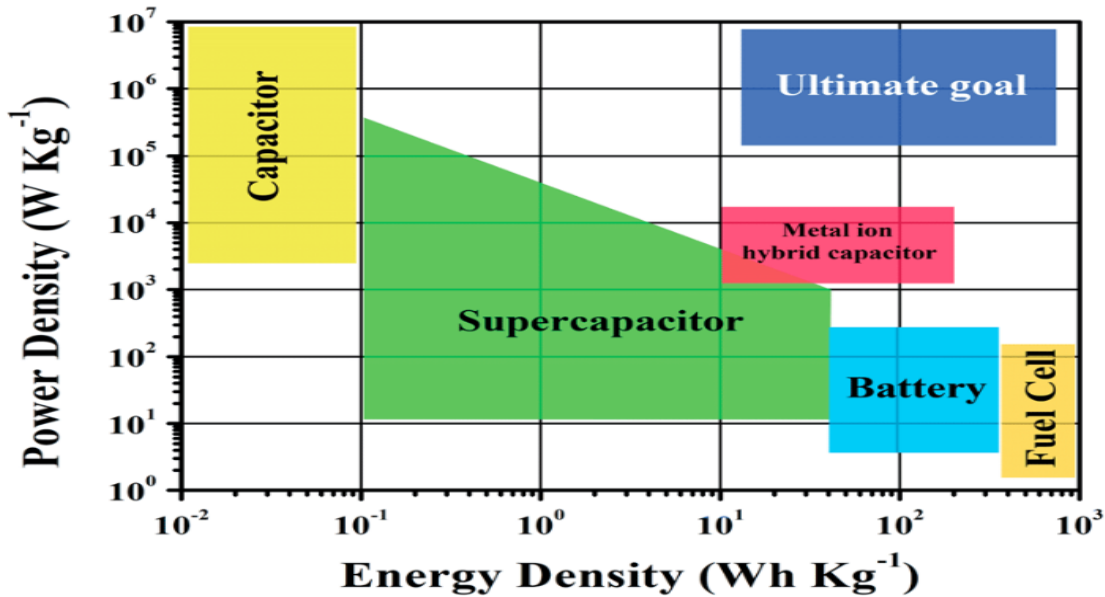


Figure 1.1. Various energy storage devices plotted in a ragone fashion [1]-

Supercapacitors, with their distinct high-power density qualities and fast charge/discharge capabilities, find applications across various fields:

Used in hybrid vehicles and electric cars for regenerative braking, helping to store and release energy efficiently during braking and acceleration. Integrated into solar or wind power systems to store excess energy and provide bursts of power when needed, aiding in smoothing out fluctuations in energy generation. They are employed in smartphones, laptops, and other portable devices for quick energy bursts during peak power demands, reducing the need for frequent charging. They Incorporated into defibrillators, pacemakers, and other medical equipment for

delivering rapid bursts of energy when required, ensuring prompt and reliable operation, and used in conjunction with batteries in energy storage systems for grid stabilization, load balancing, and maintaining power quality in smart grids [8][9].

1.2 Historical background

Supercapacitors have been the focus of research over the last few decades [1]. They offer a highly reversible, long cycling life, and power-density energy storage technology. A jar that is made up of glass with two metal foils, water, and a conductive cord served as the "Leyden Jar," which served as the prototype capacitor and marked the beginning of the history of SCs. Static electricity can be generated by spinning this pot. At the start of the 1800s, the concept of static electricity was identified. The EDLC capacitance was first brought in by **Hermann von Helmholtz** in 1853. The first patent for a double-layer capacitance structure, however, was not received by General Electric Company's Becker until 1957. This was the first time that highly specific surface area porous carbon was used as an electrode material for an electrochemical capacitor [10].

In 1970, SOHIO also received a patent for a different disc-shaped capacitor that contained carbon paste soaked in electrolyte [11]. The Nippon Electric Company (NEC) was granted a license by SOHIO to utilize this EDLC technology in 1971. NEC was able to produce the first double-layer capacitor for commercial use, which they called a "supercapacitor" [12]. With the advancement of critical technologies, the supercapacitor's industrialization phase began at that point. These included enhancing the manufacturing process, electrolyte, and electrode materials. In 1978, Panasonic developed a supercapacitor known as a "Gold capacitor" used for memory backup applications.

SCs were initially limited to using as backup memory for electronics. Material science developments have aided in the wider development of more affordable, more efficient SCs. Manufacturing of SCs began in the late 20th century with several companies. Pseudocapacitors with Faradaic processes, the second electrochemical capacitor, were identified in 1971. MP Pulsar proposed one of the earliest ASC prototypes in 1989, with a negative electrode based on AC and a positive electrode centered on Ni(OH)₂.

In 1992, Maxwell Technologies developed their own SCs, which they dubbed "Boost Caps." The CEO of Tesla, Elon Musk, predicted that SCs would power EVs in the future. To better meet potential needs, more research and development is needed to increase the supply of affordable, high-quality SCs. A thorough explanation would aid in the understanding of this topic, as we currently lack a solid understanding of the fundamental mechanism underlying charge storage for EDLCs and pseudocapacitors[13].

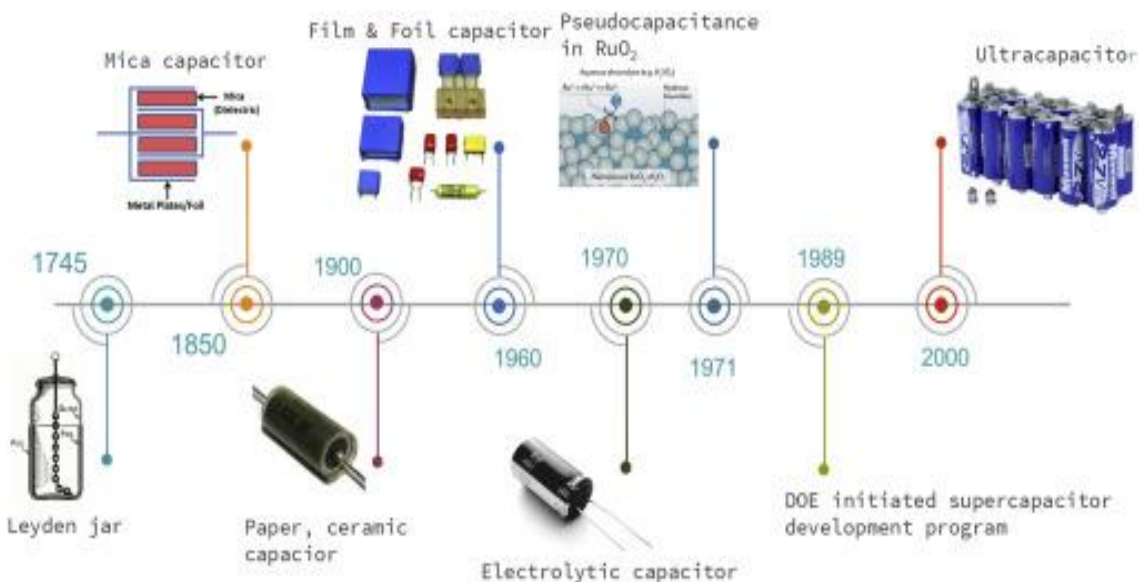


Figure 1.2 Depicts the evolution of capacitors from their historical inception to supercapacitors[14].

These days, supercapacitors are produced globally by several businesses and are in high demand. A range of EDLC components have been developed in America and Japan by companies such as Panasonic, NEC, Epcos, ELNA, Cooper, and AVX. Moreover, integrated modules with voltage balancing circuitry are produced by Evans and Maxwell. Several EDLC module types are available from ESMA in Russia for use in electric vehicle and power quality enhancement applications. These days, commercial supercapacitors are widely utilized as standby power for random access memory devices, electric hybrid cars, electric tools, communication devices, digital cameras, mobile phones, and solar cell energy storage [15][13]. They are also utilized as uninterruptible power supplies for computers.

1.3 Introduction to Supercapacitors

Supercapacitors are cutting-edge energy storage technologies distinguished by their exceptional speed at which they can store and release electrical energy. Unlike conventional capacitors, which store energy through an electrostatic field, and batteries, which store energy through chemical reactions, supercapacitors use a unique mechanism based on the principles of the electrical double layer (EDL) and, in some cases, pseudocapacitance[16]. The electrical double layer, which forms at the interface between an electrolyte and an electrode material with a high surface area, is the fundamental idea behind a supercapacitor. An EDLC is produced when a voltage is applied and ions from the electrolyte gather at the electrode-electrolyte interface. This procedure makes it possible to store electrical energy [17].

Supercapacitors are known for their exceptional properties:

High Power Density: They can deliver bursts of energy swiftly, making them ideal for applications requiring rapid charging and discharging.

Long Cycle Life: Their charge/discharge mechanism is highly reversible, allowing for thousands to even without appreciable deterioration for millions of charge-discharge cycles.

Fast Charging and Discharging: Unlike batteries, Supercapacitors have quick charging and discharging times, making them valuable for applications where quick bursts of energy are needed.

1.4 Construction and working of supercapacitor

Supercapacitors work based on a fascinating principle called the electrical double layer (EDL or EDLC), which involves gathering charge at the point where the electrolyte and electrode surface meet. This process is purely physical and doesn't involve chemical reactions or alterations in phase. It's incredibly reversible, allowing for thousands of cycles without significant degradation. Imagine a supercapacitor as a cell containing electrolyte, separated by a membrane, with two carbon-based electrodes inside [16]. These electrodes are equivalent and positioned parallel to each other, forming the core structure of the supercapacitor, as depicted in **Figure 1.3**.

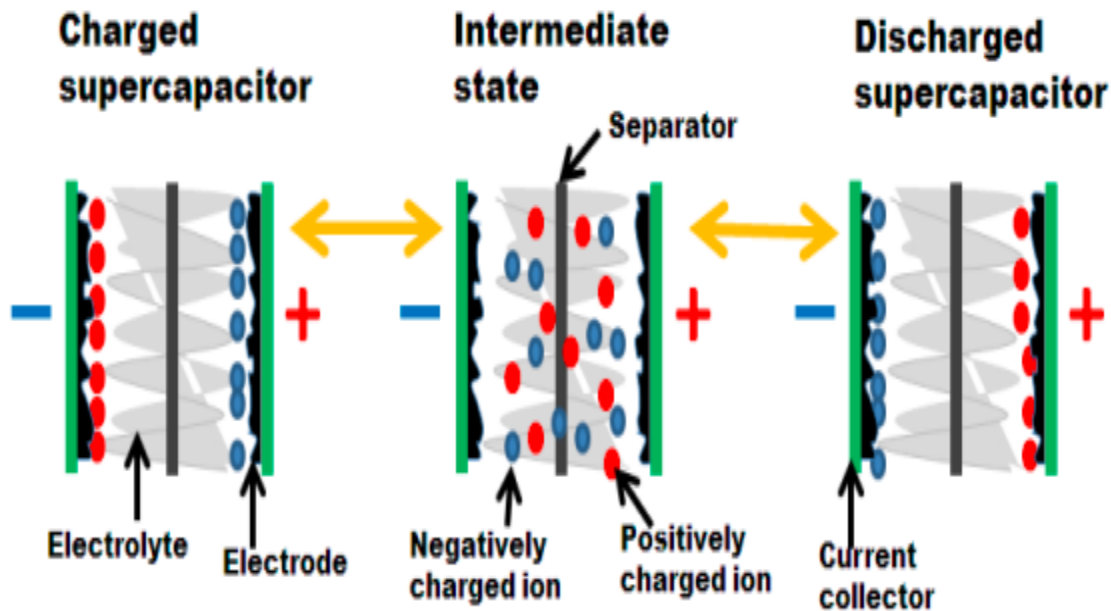


Figure 1.3 Schematic illustrations of the charging and discharging phenomena.

There is no potential difference in the open circuit. If we close the circuit and link the cell to an external power source, the current can continue to flow from one electrode to the other, creating a potential difference between the electrode and the other [18]. The charge will be distributed and collected at both ends of the cell.

In the context of supercapacitors, the electrodes play a crucial role in storing and releasing electrical energy. In a three-electrode system, distinct roles are assigned to each electrode. The reference electrode, typically crafted from standard materials like Ag/AgCl or Hg/HgCl, sets a benchmark for electrochemical measurements. Counter electrodes, commonly composed of materials such as platinum or graphite wire, are selected for their excellent resistance to corrosion. These counter electrodes facilitate the overall electrical process. The materials being studied or tested form the working electrode, where the primary

investigation into electrochemical properties takes place. However, in many scenarios, a simpler two-electrode system is preferred due to its practical advantages, streamlining the experimental setup and analysis processes [19][20].

In a two-electrode system, supercapacitors can take two distinct configurations based on the electrodes used. When both electrodes comprise the same materials, these supercapacitors are termed symmetric supercapacitors. Conversely, asymmetric supercapacitors consist of electrodes made from different suitable materials. The active materials housed within these electrodes play a crucial role in managing electric charge and storing energy during the charging process. Additionally, they facilitate the discharge of stored energy. This process is coordinated through the separator within a specific electrolyte, which aids in maintaining the integrity of the system and controlling the flow of ions between the electrodes during charge and discharge cycles [20][21].

1.5 Basic terms related to supercapacitor

Fundamental concepts like specific capacitance, energy density, and power density are used to calculate the efficiency of supercapacitors. A common metric used to describe the capacity of different electrochemical energy storage devices to hold onto electric charge is called specific capacitance (C_{sp}). Supercapacitors' energy density (E_d) measures a material's ability to store energy in relation to its mass or area. This measurement emphasizes the energy stored in the electrode materials and is derived from the galvanostatic charge-discharge process. Power density (P_d), on the other hand, describes how much energy a supercapacitor can deliver in a given amount of time. Power density is ascertained by the galvanostatic charge-discharge process, just like energy density. When taken as a whole, these metrics

provide information about the effectiveness and performance of supercapacitors, which facilitates comparison and assessment [21].

1.6 Classification of supercapacitors

Different kinds of supercapacitors can be distinguished based on the various underlying phenomena. Based on their charge storage mechanisms, supercapacitors are categorized into the following groups..

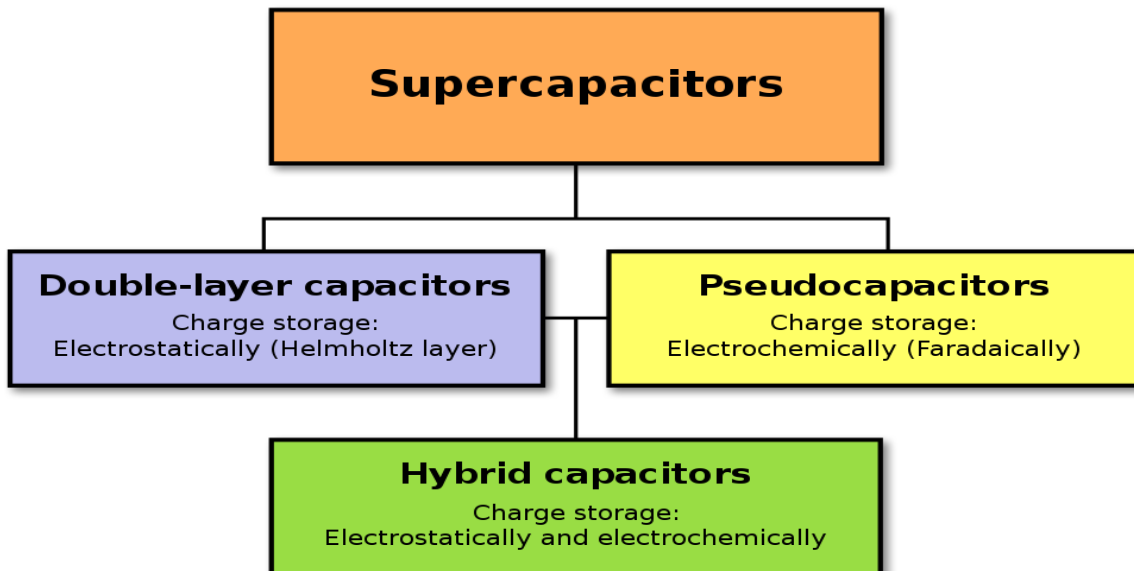


Fig 1.4 Classification of related-type capacitors and supercapacitors [22].

1.6.1 Electric Double Layer Capacitors (EDLCs)

Supercapacitors, sometimes referred to as electric double-layer capacitors (EDLCs), are cutting-edge energy storage technologies. In contrast to conventional batteries or capacitors, EDLCs store energy by separating charges at the interface between an electrolyte and high-surface-area electrodes. Rapid energy storage and release is made possible by this special mechanism, known as the electrical double

layer. The outstanding qualities of EDLCs include their high power density, which enables rapid cycles of charging and discharging; their longevity, which allows them to withstand multiple cycles of charging and discharging without appreciable degradation; and their ability to supplement or even replace batteries in certain applications because of their rapid energy delivery. The efficiency, dependability, and versatility of these supercapacitors have been repeatedly demonstrated in a wide range of applications, from transportation (such as hybrid cars) to renewable energy systems and portable electronics [23][24].

1.6.2 Pseudocapacitors

Between batteries and traditional capacitors, pseudocapacitors are an interesting class of energy-storage technologies. When compared to electric double-layer capacitors (EDLCs), pseudocapacitors store energy through the combination of fast, reversible faradaic redox reactions at the electrode-electrolyte interface and the electrical double layer. The energy density of pseudocapacitors is similar to that of batteries, but they still have the quick charge/discharge times of capacitors. These batteries and capacitors are a promising combination because they can combine the best qualities of both, providing high power and energy densities. These applications include renewable energy systems, hybrid cars, and portable electronics[21][23][24].

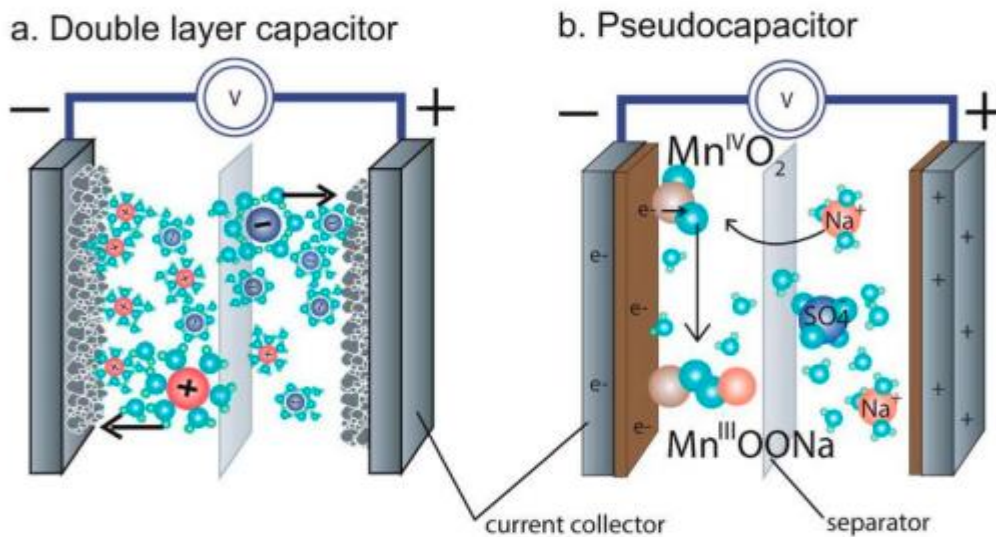


Fig 1.5 Schematic representations: (a) EDLC with carbon as the active material; (b) Pseudocapacitor with MnO₂ as the active material [25][26].

1.6.3 Hybrid supercapacitors

A significant development in energy storage technology is represented by hybrid supercapacitors, also referred to as asymmetric or hybrid capacitors. These capacitors combine the best attributes of supercapacitors and batteries to create a hybrid system that excels in both energy density and power density. By integrating a high-capacity electrode typical of batteries with a high-power-density electrode characteristic of supercapacitors, hybrid supercapacitors achieve a balance between energy storage and rapid energy delivery. This innovative combination results in a device capable of offering significantly higher energy densities than traditional supercapacitors while maintaining their ability for quick charge and discharge. Hybrid supercapacitors find application in a wide array of fields, including portable electronics, automotive systems, renewable energy storage, and various industrial applications, showcasing their potential as a versatile and efficient energy storage solution. Ongoing research and development continue to refine

these hybrid systems, paving the way for even more efficient and adaptable energy storage solutions in the future [23][24].

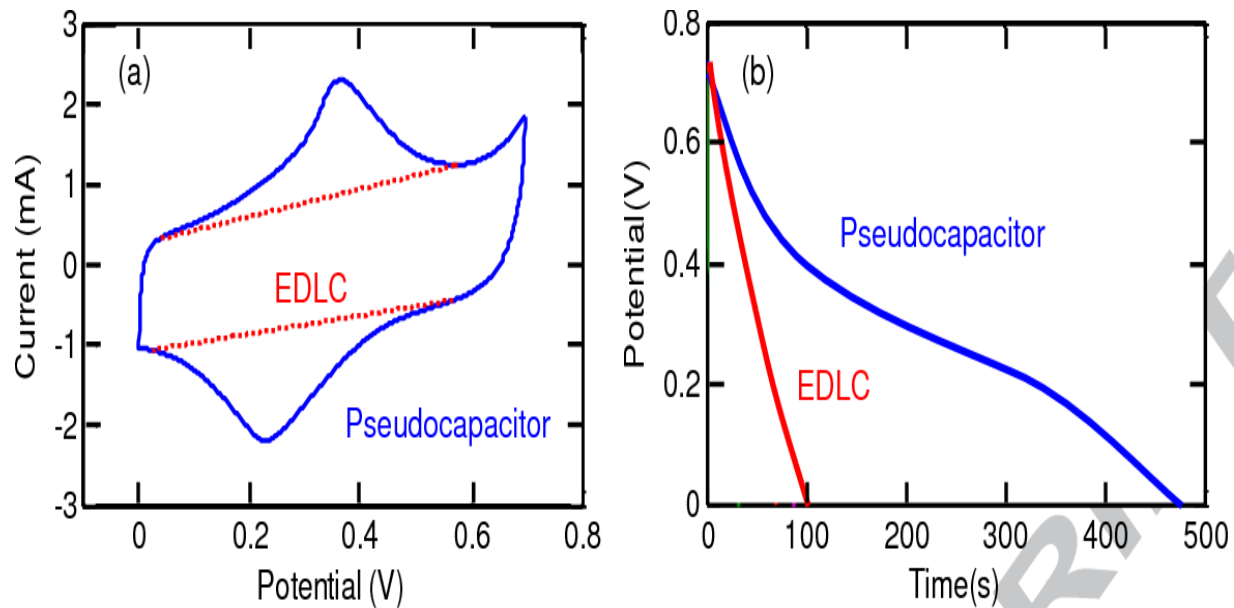


Fig. 1.6 Supercapacitor classification using cyclic voltammetry as the basis

1.7 Application of Supercapacitors

Supercapacitors, with their unique characteristics, find applications across diverse fields due to their ability to store and release energy rapidly. Some notable applications include:

1.7.1 Consumer electronic products

Supercapacitors have a range of applications within consumer electronic products, contributing to enhanced performance, efficiency, and user experience in various devices. Some notable applications include:

1.7.1.2 Main power sources

Supercapacitors can produce one or more brief (microsecond to second) large current pulses. For certain standard applications, they can serve as the primary power sources. Toy cars, for instance, have "rechargeable motors" that are made of supercapacitors that can be recharged using a battery or a charger that runs on the mains. This supercapacitor can be charged fast, giving the toy the extra power it needs to accelerate. It is possible to charge a supercapacitor with a low power rating power supply when it serves as the primary power source [13][18].

1.7.1.3 Alternate power sources

Supercapacitors were also employed in the following applications as backup power sources under various circumstances. During daylight hours, solar cells provide the electric load and simultaneously charge the supercapacitor. Throughout the night, the supercapacitor provides the electricity. A solar watch, for example, can run for several days thanks to its supercapacitor, which is charged by a solar cell. Some road marking lanterns and traffic warning signals are also powered by a solar cell and supercapacitor system, which is a dependable system with no maintenance needs and a long lifespan [1][13].

1.7.2 Vehicles applications

Supercapacitors can be used as a high-power, short-term energy-storage gadget in hybrid and electric cars, storing the energy produced by regenerative braking. We can use this energy to power the next acceleration process. In this scenario, supercapacitors can be used to reduce the size of the primary power source, which can be batteries or an internal combustion engine. For transportation vehicles like buses, delivery vans, and cars, a combination of batteries and supercapacitors can

provide a dependable energy supply system for engine starting, electric power steering, catalyst and actuator preheating, and distributed power systems.

Ships and airplanes can also use a similar combination. In addition, wheelchairs, people movers at fairs, and carriers in factories and hospitals can all be equipped with supercapacitors. They will quickly be refilled at the stations where cargo or passengers board or disembark. Reusing the braking energy will result in cost savings [1][13].

1.7.3 Industrial process

Certain industrial processes, like those in the chemical, textile, and pharmaceutical industries, are particularly vulnerable to mains voltage disruptions and interruptions. Once the power supply was interrupted, there would be a costly loss of production. For those uses, supercapacitors can offer a more stable power supply and improved energy ratio [13].

1.8 Thesis Structure

Chapter 1 of this thesis project provides an overview of the research background, types, and applications of supercapacitors. Chapter 2 examines the literature on earlier research on the kinds, compositions of the electrodes, and operation of supercapacitors in addition to their development trends. Chapter 2 also provides an update on the current status of the flexible supercapacitors project. The materials, reagents, and experimental procedures used in this thesis work are all described in Chapter 3. The electrochemical measurements, results, discussion, and conclusion of the characterization of flexible film supercapacitors are presented in Chapter 4. Chapter 5 is about conclusion and acknowledgement and chapter 6 is references.

1.9 Aim and Objectives

There are various downsides to capacitors, such as low voltage, current leakage, huge size, high cost, and low frequency. Batteries also have several drawbacks, such as a short lifespan, sensitivity to temperature changes, high cost, lengthy charging times, and negative environmental effects. To address these problems, Hybrid supercapacitors are becoming increasingly important in the field of renewable energy. Hybrid supercapacitors have high power density and high energy density, long lifespan, and are environment friendly. There are some challenges in its fabrication that need to be addressed. One of the main challenges is the difficulty in achieving a high energy density while maintaining a high power density. Another challenge is the need for high-quality materials. Carbon nanotubes and metal oxide nanowires are expensive to produce and have limited availability. The goal is to fabricate flexible electrode for the hybrid supercapacitor which has high power density, high energy density, inexpensive, eco-friendly, and scalable.

The following are the main goals of this thesis:

- **The goal is to create flexible supercapacitors with a shape and structure that adheres to the standard supercapacitor working mechanism.**
- **To produce flexible supercapacitors with inexpensive materials.**
- **To evaluate the manufactured supercapacitors' flexibility and electrochemical performance.**
- **To investigate the flexible supercapacitors' electrochemical performance under mechanical testing circumstances.**
- **The aim is to enhance and optimize both the manufacturing process and electrochemical performance of flexible supercapacitors**

Chapter 2 Literature Review

This chapter covers the literature review of flexible supercapacitor for efficient, low cost and environment friendly device.

2.1 Electric Double layer capacitors

Supercapacitors known as electric double layer supercapacitors (EDLCs) store energy at the electrode and electrolyte interface as electrostatic charge. The EDLCs store energy by physically adsorbing and desorbing ions at the interface between the electrode and electrolyte. As can be seen in **Figure 1.7**, faradic reaction plays no part in the energy storage process, and their cyclic voltammetry displays rectangular behaviors. Typically, carbonaceous materials like activated carbon make up EDLCs. Pseudocapacitors lack the power density of EDLCs. Although they charge and discharge quickly, they still face a significant challenge due to their low energy density [22][8].

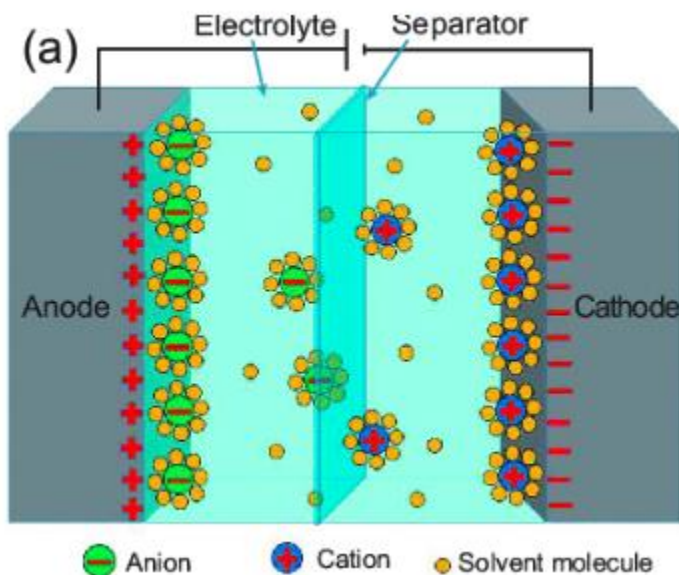


Fig.1.7 Schematic representation of (a) electrical double-layer capacitor (EDLC)

2.1.1 Supercapacitors based on activated carbon

Among the various carbon materials, ACs is particularly appealing because of their inexpensive, high specific surface area, and excellent adsorption properties when used as electrodes for capacitors. Carbon-rich precursors are carbonized and activated in an inert atmosphere, then selective oxidation in CO₂, water vapor, or KOH increases the specific surface area and pore volume of AC. **(Figure 1.8)**[27][28]. The main source of this surface area is an intricately linked web of internal pores. Three classes of pores have been identified: macropores ($d > 50$ nm), mesopores ($d < 50$ nm), and micropores ($d < 2$ nm)[29]. The Brunauer, Emmett, and Teller (BET) method is a significant analytical technique that can be used to measure the surface area of porous carbon materials. It determines a material's specific surface area by measuring the amount of adsorption of the gas that corresponds to a monomolecular layer on the surface and by physically adsorbing a gas on the solid's surface.

For instance, Lota and associates devised a basic technique utilizing KOH at 850 °C to revive a commercial air conditioner. When compared to commercial air conditioners, the reactivated materials' effective areas were significantly larger. Consequently, the reactivated carbon's specific capacitance rose to three times that of the unprocessed AC [30]. The distribution of pore sizes is also crucial. It influences the diffusion of electrolyte ions. The impact of coal-based AC's pore size distribution on double layer capacitance was investigated by Gryglewicz et al.[31].

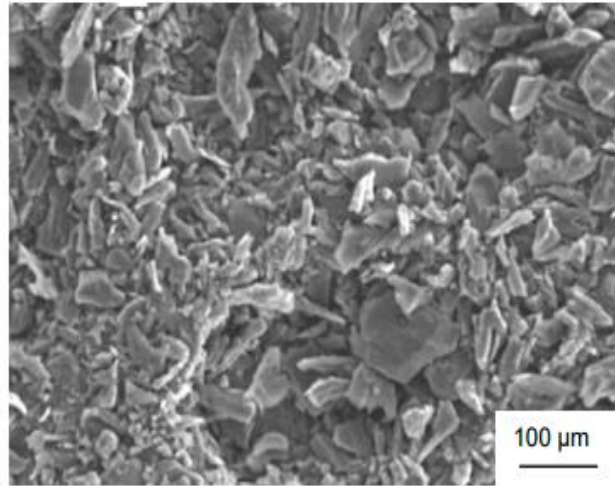


Fig 1.8 SEM of AC produced by heating and activating it with KOH [28].

As seen in Figure 1.9, the ACs with a mesopores content of 46.3–86.9% and a BET surface area up to 1000 m² g⁻¹ showed higher specific capacitance as the BET surface area increased. There was no linear correlation discovered for the ACs with surface areas greater than 1000 m²g⁻¹.

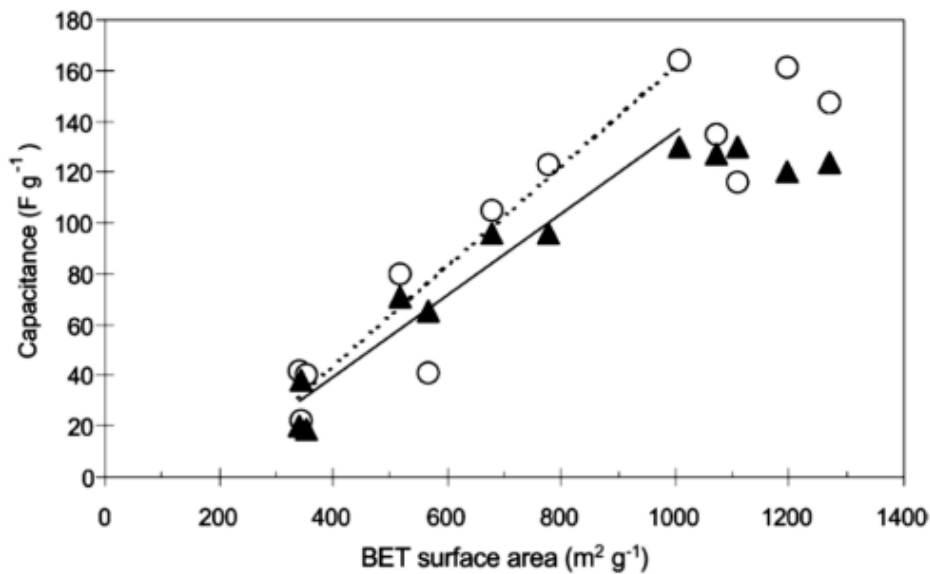


Fig.1.9 Specific capacitance for AC (O) 1 mol/L H₂SO₄ and (▲) 6 mol/L KOH z

[31].

2.1.2 Carbon aerogels and xerogel

Carbon aerogels is regarded as a potential material for supercapacitors due to its adaptable qualities, which include high porosity, fine pore size, high surface area (400-1000 m²g⁻¹), and exceptional electrical conductivity [32][33][34][35]. The remarkable properties of carbon aerogels are contributed to 3D mesoporous network of carbon nanoparticles. Using a sol-gel method, organic aerogels based on formaldehyde (RF) and resorcinol are typically pyrolysis to create carbon aerogels [36]. The activation process, temperature during pyrolysis, reaction conditions, and the presence of particular dopants are some of the synthesis parameters that can alter the aerogels' microtexture, specifically the distribution of pores and size of the particles [36][37][38].

It was discovered that after activation, the specific surface area of the carbon aerogels increased significantly, leading to a significant increase in specific capacitance. The specific capacitance of the capacitors rose while their internal resistance dropped. A more thorough investigation of the effects of the carbon dioxide activation time on the porous structure and surface of carbon aerogel was conducted by Chang et al. [39]. As shown in Figure 2.0, after activation, the surface of the carbon structure was significantly etched by carbon dioxide, and a three-dimensional interconnected network structure was preserved. Carbon aerogels were infused with a large number of micropores and mesopores through the activation of CO₂, which increased the specific surface area of the material.

Longer activation times could result in higher specific surface area. As a result, there was a significant increase in the matching specific capacitance.

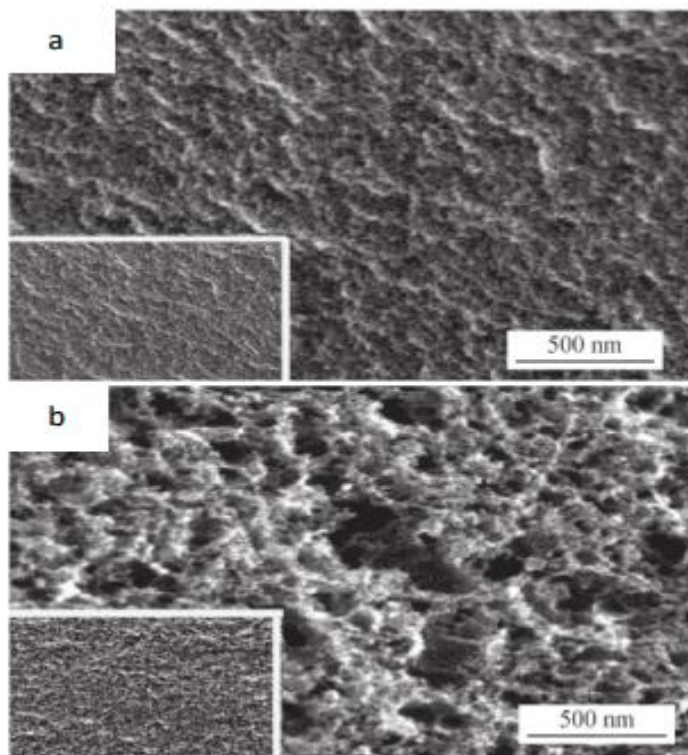


Fig.2. SEM of carbon aerogel (a) and carbon aerogel that has been activated with CO₂ for ten hours [39].

2.1.3 Carbon nanotubes based supercapacitors

Supercapacitors utilizing carbon nanotubes (CNTs) as their primary material have emerged as a promising avenue in energy storage research. CNTs offer a compelling combination of properties essential for efficient supercapacitor performance. With an extraordinarily high surface area-to-volume ratio, CNTs provide ample surface area for charge storage, while their excellent electrical conductivity facilitates rapid electron transport within the electrode material.

Additionally, their remarkable mechanical strength ensures the stability and longevity of the supercapacitor electrodes. Moreover, the chemical stability of CNTs makes them compatible with various electrolytes. Despite these advantages, challenges such as cost-effectiveness, achieving uniform distribution within electrodes, and scalability of synthesis methods remain areas of active research. Addressing these challenges could unlock the full potential of carbon nanotubes-based supercapacitors, paving the way for high-performance and sustainable energy storage solutions. Nanotubes concentrically nested like tree trunk rings (Figure 2.1b)[40]. The three most popular processes for producing SWNTs and MWNTs are laser ablation of carbon, carbon-arc discharge, and chemical vapour deposition [41].

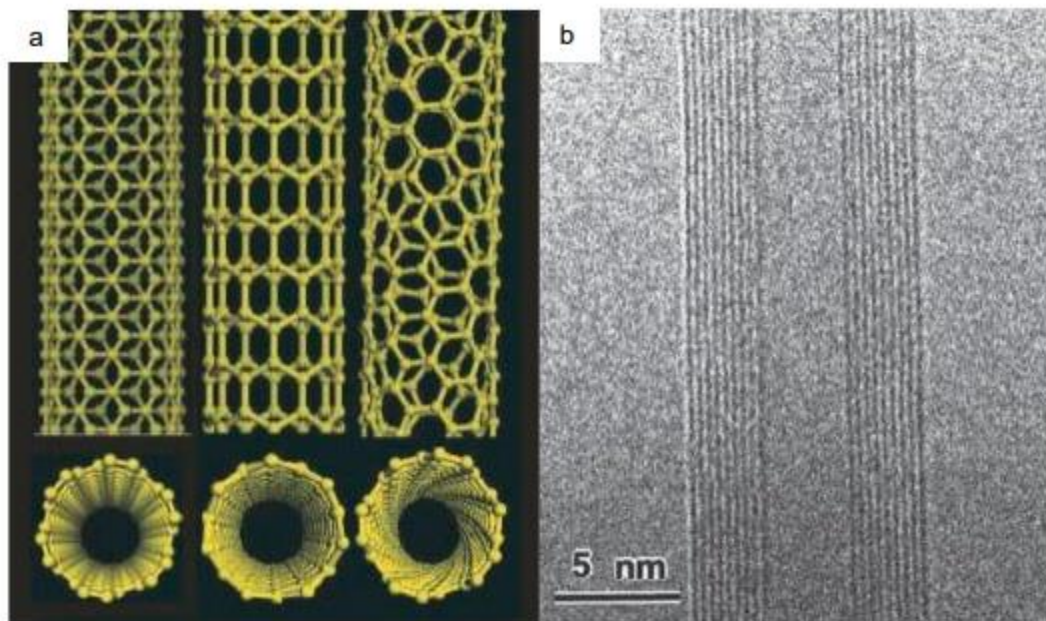


Fig 2.1 schematic representations of the three common SWNT MWNTS[40]

In general, CNTs have a smaller specific surface area than AC, which is used to make electrode materials. Scientists have devised various methods to augment the surface area in order to elevate the capacitance of carbon nanotubes number of

carbon nanotubes were used in the presence of KOH in reference [42]. The KOH activation increased the CNTs' capacitance, and because the pores were big enough to allow for ion transfer, the specific capacitance of the activated CNTs was proportionate to their specific surface area. Activated carbon nanotubes did not perform as well at a rate as raw carbon nanotubes, though. As such, further optimization of the KOH activation is required to enhance the capacitance and rate performance.

2.1.4 Supercapacitors based on graphene or graphene oxide

The amazing material known as graphene is made up of a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Renowned for its extraordinary properties, graphene exhibits exceptional strength, electrical conductivity, and flexibility. Its versatility has led to extensive exploration in various fields like electronics, medicine, and energy storage. On the other hand, graphene oxide is a derivative of graphene, created by oxidizing graphene sheets. This modification introduces oxygen-containing functional groups onto the graphene structure, altering its properties and enabling enhanced solubility in water. Graphene oxide maintains some of the properties of graphene, making it advantageous for applications in biomedical research, membranes, and composites due to its improved processability and compatibility with diverse environments. Both graphene and graphene oxide hold immense promise for revolutionizing multiple industries due to their unique characteristics and potential applications[43][44].

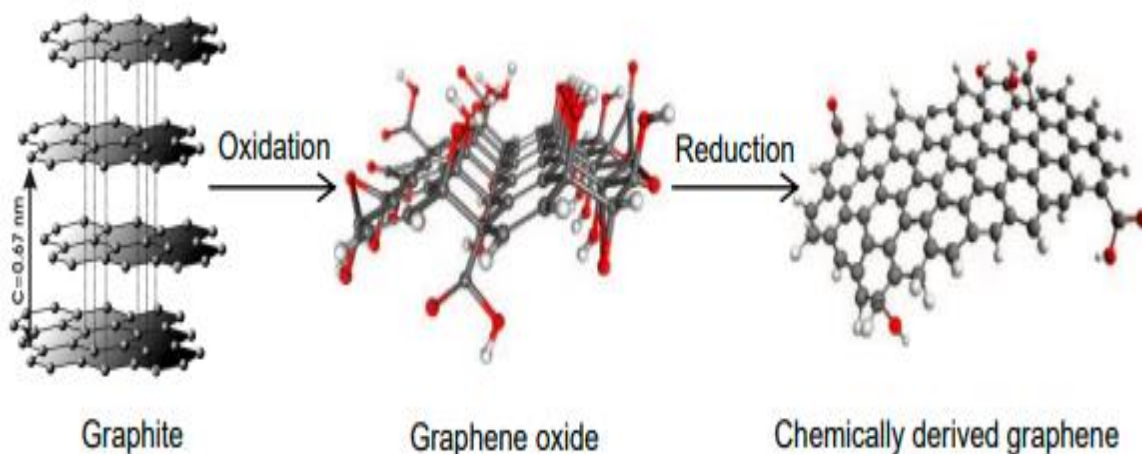


Fig. 2.2 Illustrating the chemical synthesis of graphene [46].

In the chemical synthesis process of oxidation-reduction of graphite, graphene oxide is an intermediary. Graphene oxide, as a single sheet, has some oxygen functional groups on its edges and basal planes [47], which help to provide extra pseudocapacitance in supercapacitance. Graphene oxide has a higher capacitance than graphene, up to 190Fg⁻¹, despite having a smaller surface area than graphene. This is likely due to functional groups on the oxide's surface that contain oxygen [48]. Graphene oxide is thought to be a superior option than graphene for the electrode material in supercapacitors due to its low cost and high performance [48].

2.2 Pseudocapacitors

A type of energy storage device that bridges the gap between capacitors and batteries is called a pseudocapacitor. Unlike conventional capacitors relying on electrostatic charge storage, pseudocapacitors store energy through a fast and reversible redox (reduction-oxidation) reaction occurring at the electrode surface. This process involves faradaic reactions, enabling them to deliver higher energy densities compared to standard capacitors. Transition metal oxides, conducting

polymers, or metal oxides are frequently used as active components in the electrodes of pseudocapacitors. Their ability to combine the rapid charge/discharge capabilities of capacitors with the higher energy densities of batteries makes pseudocapacitors promising for various applications in energy storage systems, portable electronics, hybrid vehicles, and renewable energy technologies, contributing to advancements in efficient and sustainable energy storage solutions [26, 27].

2.2.1 Metal oxide based supercapacitors

Metal oxides have garnered significant attention as electrode materials in supercapacitors due to its abundance, and relatively low cost. The pseudocapacitive behavior is exhibited by transition metal oxides such as cobalt oxide, manganese oxide, nickel oxide, and ruthenium oxide allowing them to store charge through reversible faradaic redox reactions. These materials possess a wide range of redox potentials and high specific capacitances, contributing to their suitability for energy storage applications. Additionally, metal oxides can offer enhanced electrochemical performance and stability in comparison to carbon-based electrodes. While challenges such as limited electrical conductivity and volume changes during cycling remain, ongoing research aims to optimize the design and nanostructuring of metal oxides to improve their overall performance and make them more practical for use in high-performance supercapacitors with increased energy density and cycling stability [49][50].

2.2.2 Conducting polymer based supercapacitors

Conducting polymers are another popular type of electrode material. They are less expensive than metal oxides and have comparable qualities to carbon-based electrode materials, such as high conductivity, low equivalent series resistance, and relatively high capacitance [51].

Different from conventional insulating polymers, conducting polymers are a class of materials with exceptional electrical conductivity and special qualities. Conducting polymers are different from other types of polymers because they can conduct electricity and still be flexible and easily processed. The conjugated structures in these materials facilitate the flow of charge carriers, which gives rise to their conductivity. They have a wide range of applications in electronics, energy storage, sensors, actuators, and biomedical devices because their electrical properties can be tailored through chemical modifications, doping, or synthesis methods. Several conducting polymers are widely recognized, such as polypyrrole (PPy), polyaniline (PANI), and polythiophene (PTh). These polymers possess unique attributes and benefits that make them appropriate for a range of technological applications. Due to their special combination of electrical, mechanical, and chemical properties, conducting polymers continue to garner a lot of interest in both research and industry, with great potential for future innovations [52][53][54].

Conducting polymers are a class of materials that are well-known for having special electrical and electrochemical properties that allow them to be used in a variety of applications, including sensors, electronics, and energy storage. Among them, polypyrrole (PPy) exhibits preference over other conducting polymers for a number of reasons. Because of its inherent qualities, which include excellent

chemical and electrochemical stability, high electrical conductivity, good environmental stability, and ease of synthesis, PPy exhibits notable advantages.

Its versatility allows for modifications in structure and properties through dopants, facilitating tailored designs for specific applications. Moreover, PPy possesses a superior redox behavior, maintaining stable conductivity even after numerous charge/discharge cycles. These attributes collectively make polypyrrole a preferred choice among conducting polymers, showcasing promise and potential for an array of advanced technological applications [55].

2.3 Hybrid supercapacitors

Based on their electrode configuration, hybrid supercapacitors can be divided into three categories: battery-type hybrids, composite hybrids, and asymmetric hybrids. An EDLC electrode and a pseudocapacitor electrode make up asymmetric hybrids[56][57][58]. For instance, Arbizzani and associates created a novel hybrid supercapacitor in 2001 by utilizing AC as the negative electrode and a p-doped polymer as the positive electrode[56]. This hybrid supercapacitor stored energy using both non-faradaic and faradaic processes, resulting in good specific power and noticeably higher specific energy. Comparable pseudocapacitors lack the cycling stability of asymmetric hybrid supercapacitors. Compared to equivalent EDLCs, they can reach higher energy and power densities.

Unlike asymmetric hybrid supercapacitors, composite hybrid supercapacitors integrate carbon materials with conducting polymers or metal oxides as electrode materials using composite materials [59]. A high surface area backbone can be supplied by porous carbon materials to improve the contact between the electrolyte and conducting polymer or metal oxide materials. Through faradaic reactions, conducting polymer materials or metal oxides can further increase capacitance.

Supercapacitor and battery electrodes are the two separate electrodes that make up battery-type hybrids [59]. This represents the third type of hybrids. Batteries displayed higher energy densities than supercapacitors, but supercapacitors had higher 24 power densities than batteries.

2.4 Flexible Electrodes

Flexible electrodes play a pivotal role in modern technological advancements, offering versatility and adaptability across various applications. These electrodes are engineered to conform and bend without compromising their functionality, making them suitable for wearable electronics, flexible displays, biomedical devices, and energy storage systems. Typically fabricated using flexible substrates like polymers, fabrics, or thin metal foils, these electrodes provide a robust platform for integrating functional materials such as conductive polymers, carbon-based materials (like graphene or carbon nanotubes), and metal oxides. Their flexibility makes them perfect for wearable sensors and medical devices because it permits conformal contact with irregular surfaces and comfortable interaction with the human body. The advancement of flexible electrodes has sparked innovation across various industries, with the potential to yield significant progress in areas that require improved performance, durability, and conformance [60][61].

2.4.1 Carbon flexible electrodes

Because of their special qualities and versatility, carbon-based flexible electrodes are a major advancement in the fields of electronics and energy storage. These electrodes provide excellent mechanical robustness, high electrical conductivity, and flexibility by utilizing different forms of carbon, such as graphene, carbon nanotubes, or carbon fibers. Because of their structural adaptability, they can be incorporated into stretchable and flexible substrates to enable conformal contact

with uneven surfaces or wearable technology. Carbon flexible electrodes exhibit outstanding electrochemical performance, making them ideal for applications in supercapacitors, batteries, sensors, and wearable electronics. Their lightweight nature, combined with excellent electrochemical properties, positions carbon-based flexible electrodes as key components for the development of next-generation, high-performance and adaptable electronic devices with a wide range of applications in diverse industries [62][63].

Carbon nanotubes (CNTs), in particular single-walled carbon nanotubes (SWCNT), are excellent active materials by nature. Kang et al. [63] used CNTs, ordinary office paper, and an silica gel electrolyte to create innovative all-solid-state flexible supercapacitors. This solid-state flexible supercapacitor performed well electrochemically and exhibited high flexibility and stability.

2.4.2 Conducting polymers electrodes

Conducting polymer electrodes serve as essential components in various electrochemical devices due to their unique properties, including high electrical conductivity, tunable redox behavior, and facile synthesis. These electrodes, formed from poly(3,4-ethylenedioxythiophene) (PEDOT), polypyrrole (PPy), and polyaniline (PANI) are examples of polymers possess versatile electrochemical characteristics that make them promising candidates for applications in batteries, supercapacitors, sensors, and electrochemical actuators. PANI, for instance, demonstrates remarkable electroactivity and environmental stability, making it suitable for energy storage applications such as supercapacitors and batteries[59].

Flexible Polyvinyl alcohol (PVA)/silver aluminum oxide (AgAlO_2) reduced graphene oxide (rGO) nanocomposite (NCs) were created using a scalable, environmentally friendly solution casting method with varying nanoparticles

loading doses. The characteristics of the prepared NCs were evaluated for wearable and flexible supercapacitor applications [64]. The all-solid-state supercapacitor demonstrated an energy density of approximately 0.01 Wh/cm³ and a power density of roughly 3W/cm³. Compared to most other conducting polymers, PPy frequently exhibits a higher mass density and a higher degree of flexibility. For example, in MnO₂/PPy/MnO₂ triple-walled nanotubes arrays, it can transport electrons and ions [65].

2.4.3 Carbon composite electrodes

In general, single carbon electrodes have low specific capacitance values. By plating the pseudocapacitive materials onto the carbon, flexible electrodes with higher specific capacitance can be produced because the pseudocapacitive materials store energy through a quick and highly reversible faradic reaction. The graphene/PPy nanofibers can be prepared by electrospinning, this showed a high specific capacitance of 140.3F/g [66].

Using a PVA/H₃PO₄ gel electrolyte, a highly flexible solid-state supercapacitor was created with a power density of 15 kW/kg and an energy density of 4.9 Wh/kg by Yuan et al. [67]. Electrochemical deposition was used to create the carbon nanoparticles and MnO₂ nanorod electrodes.

Chapter 3 Methodology

This chapter includes a description of the general materials, methodology, experimental designs, and specific equipment used in this thesis.

3.1 Reagents and apparatus

3.1.1. Chemicals

Balsa wood strips 2cmx7cm (purchased from china), Sodium hydroxide (Sigma-Aldrich), Sodium sulphite (Sigma-Aldrich), Hydrogen peroxide solution 34.5-36.5% (Sigma-Aldrich), DI water, Ethanol 99.8% (Sigma-Aldrich), Graphite powder (Sigma-Aldrich), Sulphuric Acid 98% (Sigma-Aldrich), Potassium permanganate (Sigma-Aldrich), Hydrochloric acid 37% (Sigma-Aldrich), Pyrrole monomer (Sigma-Aldrich), Hydrazine monohydrate (Sigma-Aldrich), Ammonium persulfate 99% (Sigma-Aldrich), Poly (vinyl alcohol) 87-89% hydrolyzed (Sigma-Aldrich).

3.1.2 Apparatus

The following general apparatus is used to prepare materials and measure electrochemical performance: Bibby Scientific Limited produced the JENWAY 1000 model Hot Plate & Magnetic Stirrer. China-based Biobase Company produced the oven. DAWE 43 Instruments Limited was the manufacturer of Ultrasonicator (DAWE). The manufacturer of the centrifuge, 80-2B, was Biobase.

3.2 Experiment

3.2.1 Synthesis of Graphene oxide

Using a modified version of Hummer's method, graphite powder was used to create GO. In summary, at room temperature 200mL of concentrated H₂SO₄ was first mixed with 4.0 g of graphite powder. The mixture was stirred while being cooled to 5 °C in an ice bath, and it remained below that temperature for 30 minutes. After that, KMnO₄ (16.0 g) was gradually added while stirring and the mixture was cooled so that the mixture's temperature did not rise above 10 °C. This allowed the mixture to become homogenous. 200mL of distilled water was added to the mixture above, and it was stirred for two hours at room temperature before being further diluted to 600mL of distilled water.

In order to reduce the remaining KMnO₄ in the reaction mixture, 20mL of 30% H₂O₂ was added while the mixture was being stirred continuously. This caused the color to change to bright yellow. After filtering, the solid was repeatedly cleaned with 800mL of 5% aqueous HCl to eliminate metal ions, and then it was treated with distilled water until pH 6 was reached. After that, GO sheets were exfoliated using 200 W of ultrasonication at room temperature for one to two hours. This produced graphite oxide. After GO's yellow-brown aqueous suspension was obtained, it was dried and kept at room temperature [68].

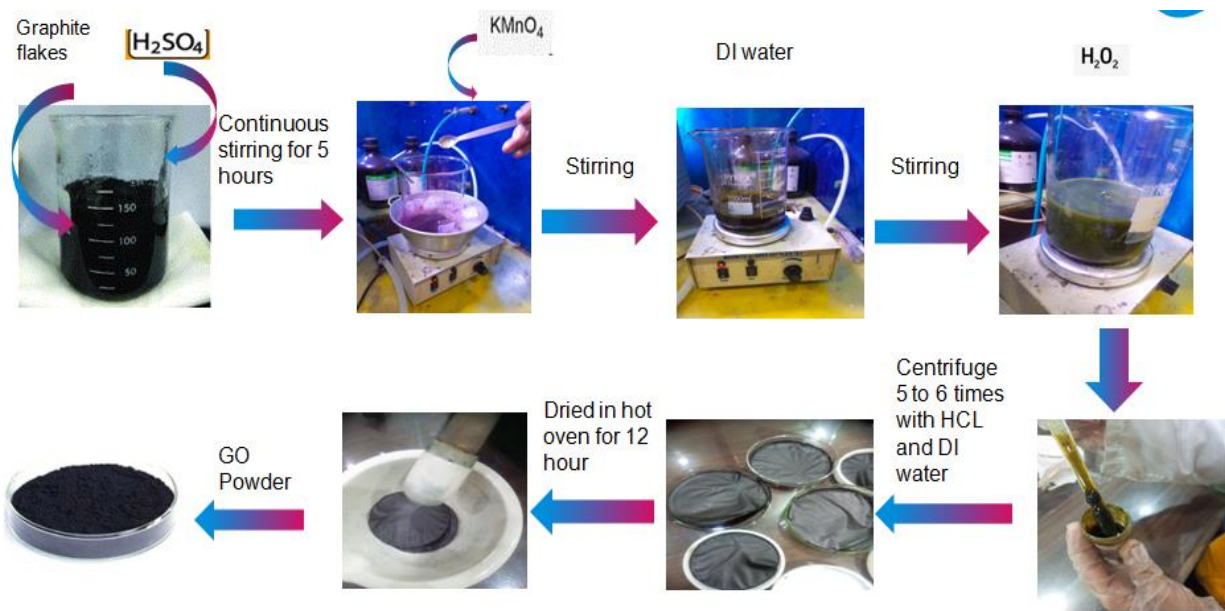


Fig 2.3 Synthesis of Go

3.2.2 Reduction of Graphene Oxide

We used the Stankovich et al. to reduce the graphene oxide. In this process, a round-bottom flask containing 100 mg of GO was filled with 100mL of deionized water. After that, the brown, inhomogeneous mixture was subjected to a 1hr sonication cycle until it cleared up and showed no signs of particulate matter. Following the addition of 1.0mL of hydrazine hydrate (32 mmol) to the solution, the mixture refluxed for 24 hours at 100 °C. The resulting black precipitate was vacuum-filtered, repeatedly cleaned with distilled water and methanol, and allowed to dry for 24hrs at room temperature [69].

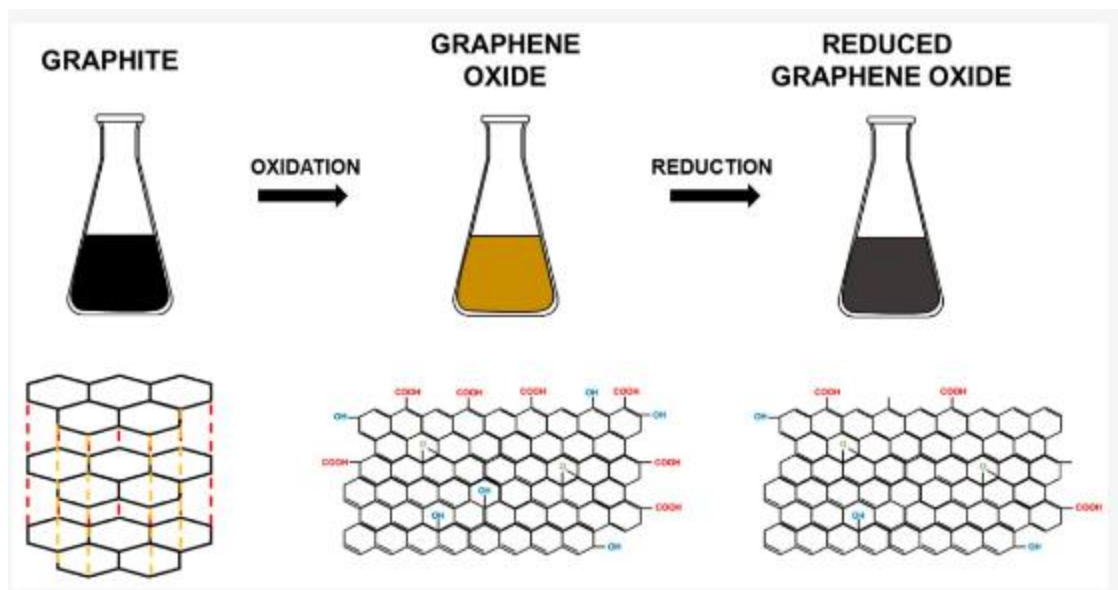


Fig. 2.4 Representation of the GO and rGO production process

3.2.3 Delignification of balsa wood

Here we used two step delignification process, prepare the solution of NaOH (2.5mol/L) and Na₂SO₄ (0.4mol/L) in the deionized water and immerse the wood chips in boiling solution for 12 hrs. The bleaching solution (H₂O₂ (2.5 mol/L) in deionized water) was then added to the wood blocks, and boiling was maintained without stirring. The samples were taken out, rinsed in cold water, and stored in ethanol when their yellow hue vanished. The flexible balsa wood template is prepared for use [70].

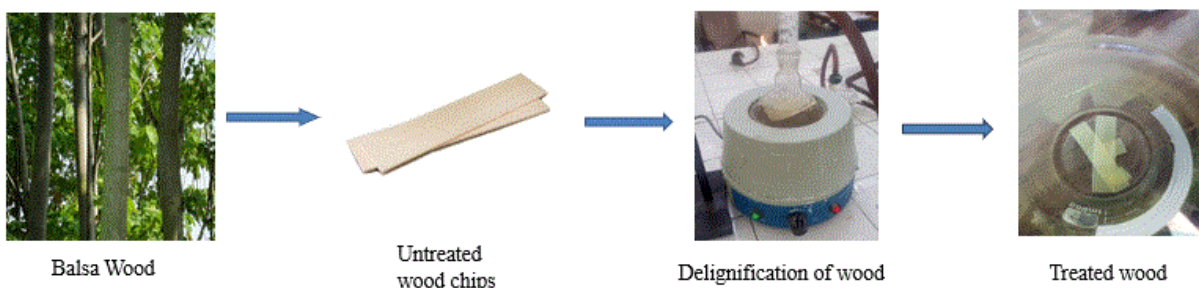


Fig 2.5 (a) Delignification process



Fig. 2.5 (b) Practical demonstration of mechanical strength and flexibility for Flexible Wood. It shows that the flexible balsa wood can be totally recovered after bending.

3.2.4 Oxidative Polymerization of Pyrrole

After 20 minutes of stirring, 2.08 mL (0.03 mol) of pyrrole was dissolved into 75 mL (1 mol/L) of HCl solution. After transferring the mixture into three neck flasks, mix it further in a cold water bath (6–8°C). 6.846 g (0.03 mol) of APS was dissolved in 75 mL (1 mol/L) of HCl solution, dropped into the flask, and stirred for 24 hours. After filtering the mixture, the residue underwent three thorough washings with ethanol and deionized water, respectively. The resulting powders were dried for at least 24 hours at 60°C. Now the fine black powder of polypyrrole is ready to use [71].

3.2.5 Preparation of polypyrrole, reduce graphene oxide, and PVA solution (10%)

PVA powder was dissolved in 10% weight-per-volume DI water to make a PVA solution. After two hours of gentle stirring and temperature maintenance of 80–90°C, the solution was found to be entirely dissolved of PVA powder [72]. After ultrasonically preparing reduce graphene oxide (rGO, 0.04 g) for 15 minutes, the mixture was added to an ionic PVA solution. A PVA ionic solution (10% by weight) was made in 12 milliliters of DI water. Polypyrrole (PPy, 0.04 g) was prepared in water solution (4 ml) and added to PVA/GO solution, mixing for one night to create GO/PPy/PVA (1:1:3) viscous solution [73].

3.2.6 Formation of nanofibers by electrospinning method

For the preparation of nanofibers, an electrospinning machine was employed. Using a 5ml syringe filled with the polymer solution, the needle was electrospun at a voltage 18kv by means of a high-voltage power outlet. In order to operate the device, the needle tip was adjusted to be 15 cm between the plates on which the flexible wood template is placed, with a flow rate of 0.3 ml/h. Once 5hrs had passed, the process was finished by keeping the nanofibers coated template in the vacuum oven at 40°C for 6 hours. At the end about 200-400 nm is the size of the nanofibers[66].The material coat on substrate is about 0.4g.

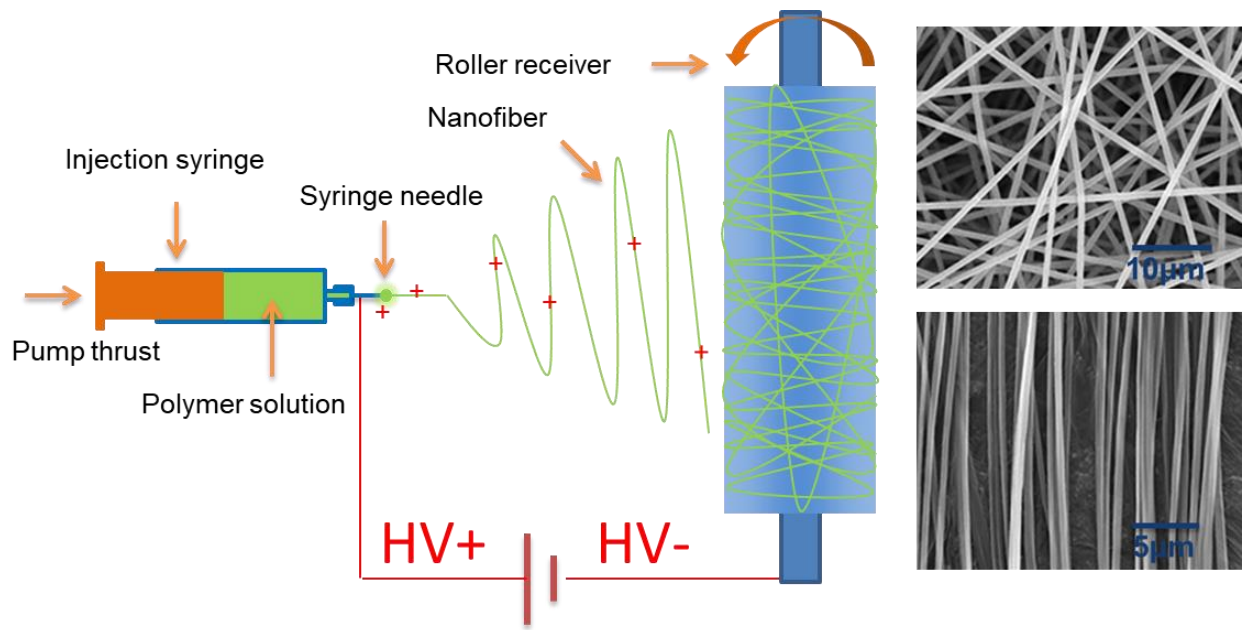


Fig 2.6 (a) Graphically representation of Electrospinning process



Fig 2.6 (b) Prepared Flexible Elect

Chapter 4 Results and discussion

4.1 SEM analysis

Utilizing scanning electron microscopy (SEM), one can examine the surface morphological features. The scanning electron microscope (SEM), invented by Manfred Von Ardenne in 1937, achieved high magnification by scanning the specimen's surface with a focused electron beam. Resolved specimen surface areas with an intense electron beam (200 V to 100 KV) can reach up to 1 nm. The fundamental elements of SEM are displayed in Figure 3.4. The anode and magnetic lenses are used to control the primary electron beam, which is produced by the electron gun. The primary electron beam is made parallel by the anode and is focused into the specimen vacuum region by the magnetic lenses

Different kinds of emitted signals, which provide particular information, can be diagnosed by different kinds of detectors. For instance, diffracted electrons can show the crystals' orientations and structure, and SEM images can be produced by secondary electrons and backscattered electrons. The elemental composition of the surface can be ascertained by utilizing auger electrons, which are low energy electrons that are characteristics of surface atoms. As a result, surface topography and grain size can be determined using the measured SEM images. SEM can also show how the chemical composition varies spatially by characterizing the elemental maps. Any field where solid material surface characterization is required can use it. Most SEMs are relatively simple to use and don't take much effort [74][75].

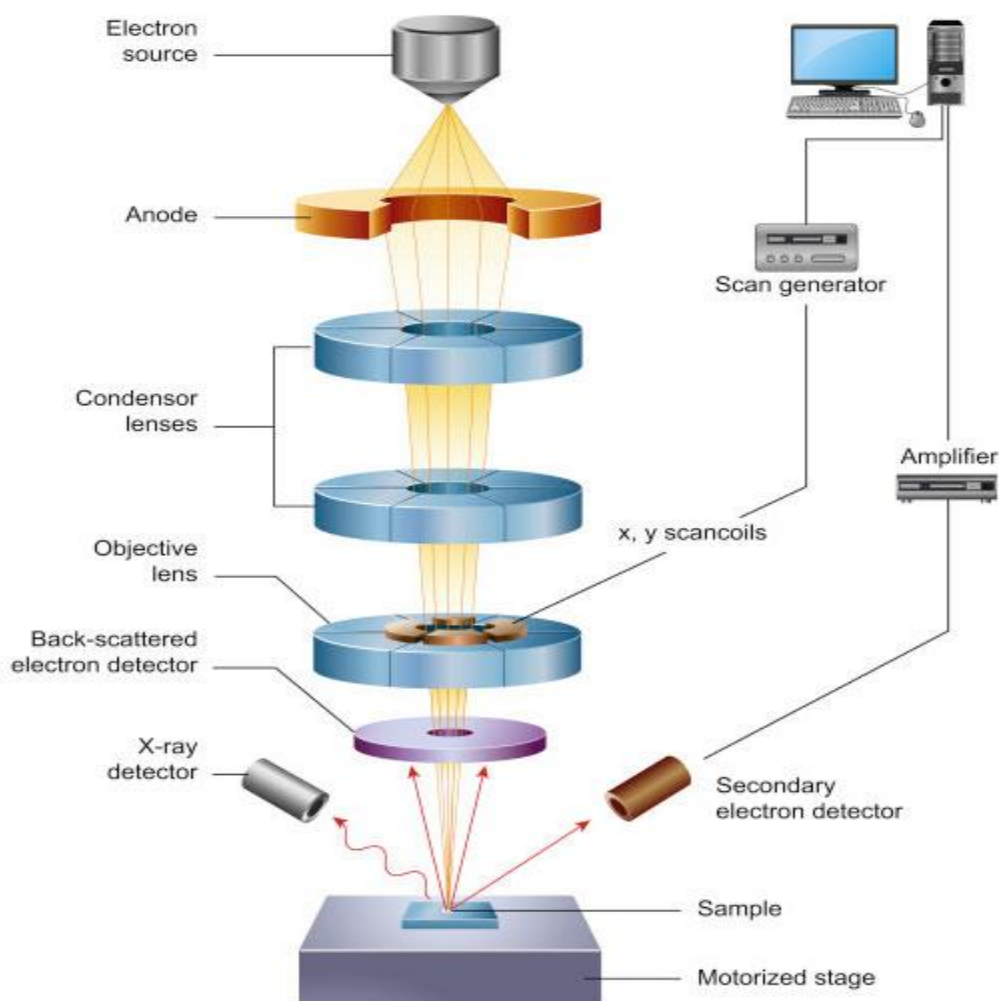


Fig 2.7 Schematic of a scanning electron microscope [75].

The world's lightest and fastest-growing tree, balsa wood has been planted across a wide region in China's southern regions (Fujian, Yunnan, Guangdong, etc.). The wood's cell walls are made up of three different chemical structural elements: (i) cellulose, a fibrous linear polymer derived from glucose units; (ii) hemicelluloses, a heteropolymer composed of shorter polysaccharides; and (iii) lignin, a three-dimensional complex amorphous polymer derived from phenylpropane units. The

SEM images of delignified balsa wood are displayed in Figure 2.9.

The three-dimensional (3D) balsa wood mesopores provided a lot of porosity for ion exchange during the electrochemical reaction. The tiny channels allow ions to flow through the channel more easily. Well-aligned straight channels (10-50 μm) are visible in the sectional SEM images of balsa wood. The porous structure along the channels of the hierarchical 3D scaffold facilitates the rapid penetration of electrolyte [76][77]. It also helps to create an incredibly conductive platform for charge collection and a highly synergistic effect. According to reports, these structures exhibit superior capacitance and longevity in electrochemical storage.

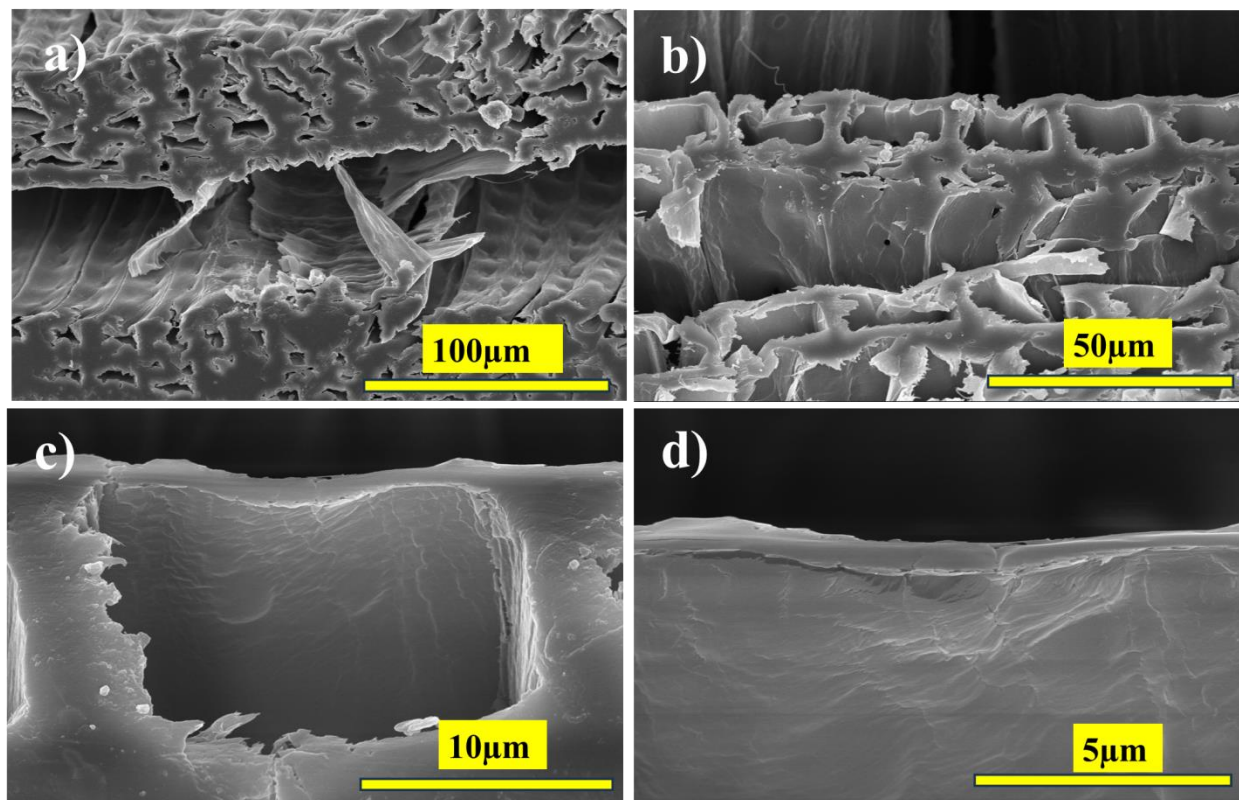


Fig.2.8 SEM images of Delignified Balsa wood at different resolution (a) at 100 μm (b) at 50 μm (c) 10 μm single channel view (d) 5 μm surface view of DBW

4.2 Electrochemical performance

4.2.1 Cyclic voltammetry (CV)

Corrtest electrochemical workstation (China) was used to evaluate the electrochemical performances of electrodes. A standard three-cell electrode, a platinum wire as a counter electrode, Ag/AgCl electrode as a reference electrode with an aqueous electrolyte (0.06M CuCl₂+1M HNO₃) was used to carry out performance test of the working electrode. The synthesized nanofibers coated flexible balsa wood chips (2cmx2cm) were used to perform cyclic voltammetry, Galvanostatic Charge/Discharge (GCD), and Electrochemical Impedance Spectroscopy (EIS). Specific capacitances of all materials were calculated in the following Eq. (1)[78].

$$C_{sp} = \frac{\int I x dv}{\rho x m x \Delta v} \quad (1)$$

The specific capacitance (F/g) in this formula is represented by C_{sp}, the scan rate (V/s), the potential range (V), the discharge current (A), and the total mass of the electrode active materials (m).

At constant current density values, such as 0.02, 0.03, 0.04, 0.05mA/g, GCD measurements were conducted. Using Eq. 2 and the GCD method, one can determine the specific capacitance (C_{sp}) of the nanocomposites under constant current conditions [79].

$$C_{sp} = \frac{I \times \Delta t}{m \times \Delta V} \quad (2)$$

this formula, I is the constant discharge current density (A/g), Δt is the discharge time, ΔV is the voltage drop that occurs after the discharge process, and m is the total mass of the electrode active materials (g). The area under the anodic curves of the CV plot is correlated with the charge stored in the nanocomposite materials, which determines their capacity. The redox peaks show due to the oxidation and reduction reaction on the surface of electrode due to its interaction with redox electrolyte CuCl_2 and HNO_3 also rGo has different functional groups present in it like oxygen, epoxy, carbonyl and has π - π interaction for physical and chemical adsorption [55].

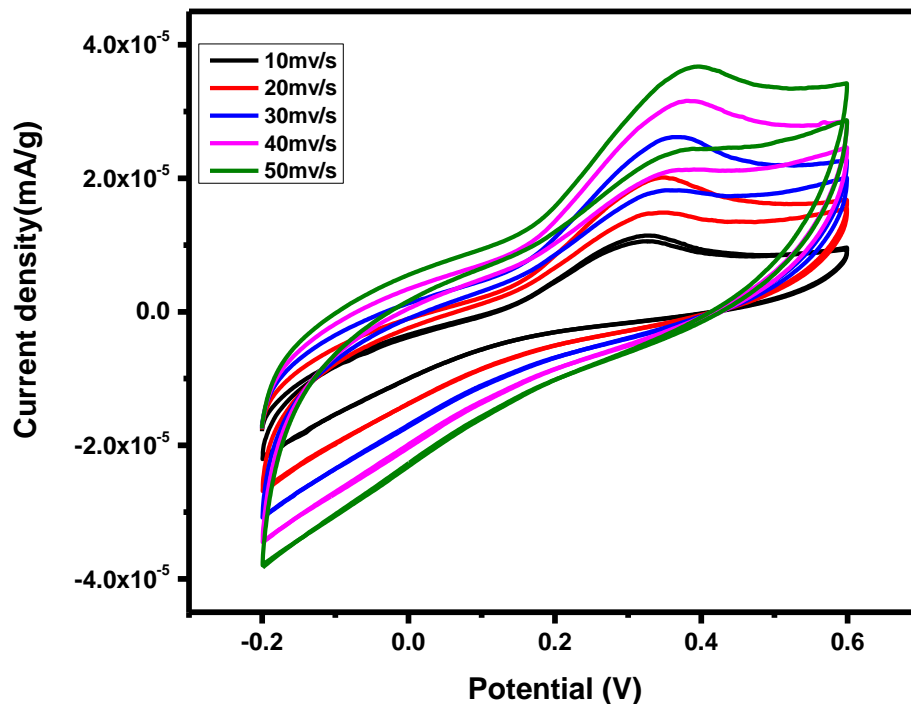


Fig 2.9 CV plot of Delignified balsa wood@rGo@Ppy at different scan rates 10mv/s, 20mv/s, 30mv/s, 40mv/s, and 50mv/s

4.2.2. Galvanostatic Charge/Discharge (GCD)

Charge/discharge curves for galvanostatic processes were measured at constant currents of 0.02mA to 0.05mA. Based on the linear part of the discharge curve, the discharge capacitance ($C_{\text{discharge}}$) was calculated using Eq. (2) [85, 86]. Excellent charge/discharge images from GCD plots are shown in Figure 3.0. The GCD method revealed that the composites of DBW/rGO/Ppy nanofibers had the highest specific capacitance, $C_{\text{sp}}= 40 \text{ F/g}$. The greatest specific capacitance was attained at low scan rates due to the low electrolyte ion diffusion in the anodic and cathodic compartments of supercapacitors (Fig. 3.0). In the nanofiber composites, ions have more time to travel around freely at low scan rates. However, at high scan rates, the amount of time that ions can be stored on the materials is limited by ion diffusion [55].

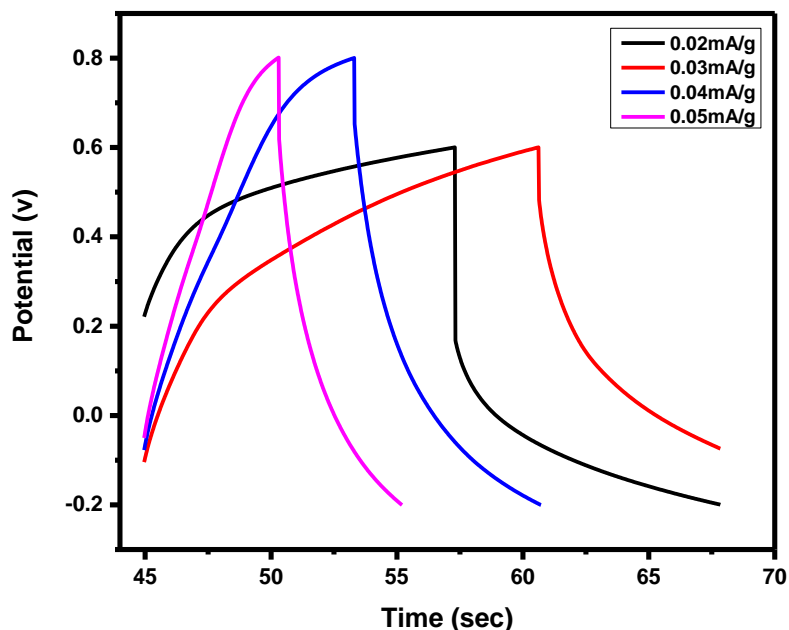


Fig.3.0 GCD curves of DBW@rGo@Ppy at different scan rates

4.2.3. Electrochemical Impedance Spectroscopy (EIS)

The process of performing electrochemical impedance spectroscopic (EIS) measurements involved gathering impedance data in order to create Nyquist plots. The Corrtest model potentiostat/galvanostat was utilized to obtain EIS measurements in order to design a two-electrode supercapacitor system at the open circuit potential using a 0.06M CuCl₂ and 1M HNO₃ solution. They are carried out across a wide frequency range (10 mHz–100 kHz) at a low voltage amplitude of 10 mV. The carriage process or ionic mass diffusion is explained by the linear portion in Figure 3.1 [93, 94]. Lower resistance to ion transfer and consequently higher capacitance are the outcomes of decreased charge density in the electrolyte [55].

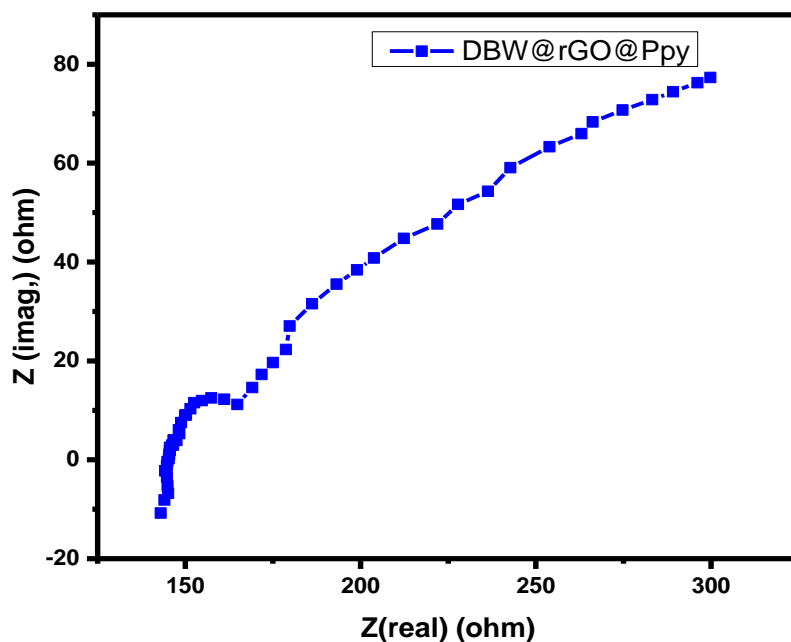


Fig.

3.1 Nyquist plot of DBW@rGo@Ppy

4.3 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR-ATR spectrum of the Graphite powder, GO/rGo is shown in Fig. 3.2. The peak at 1010cm^{-1} is attributed to C-O stretching. The peak at 1370cm^{-1} attributed as C=C and the carbonyl groups are also shown at 1664cm^{-1} as C=O stretching. The presence of a substantial number of oxygen functional groups following the oxidation process is confirmed by the high intensity of the main peaks in XGO. Adsorbed water molecules' vibrations are linked to the peak at 1664cm^{-1} .

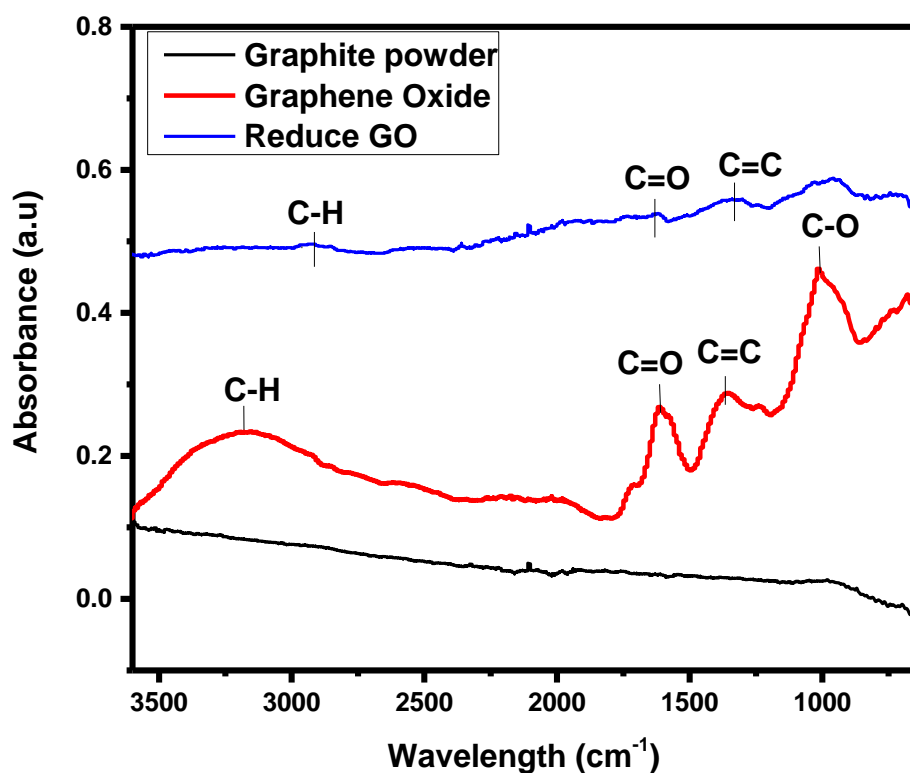


Fig. 3.2 FTIR spectrum of graphite powder, graphene oxide and reduce Graphene oxide

Figure 3.3 shows the FTIR spectroscopy-measured absorption spectra of the delignified wood (DW) and natural wood in the wavenumber range of 4000 – 400 cm^{-1} . The wavelength 1025 cm^{-1} corresponds to the greatest absorption peak of natural wood and is in the atmospheric windows. The stretching vibration of the C–O bond, which connects the OH group and C atom in the glucose ring of cellulose, is the source of this absorption peak [80]. The C–O vibration of the syringyl ring in lignin molecules is linked to the peak location at 1235 cm^{-1} [80]. The lignin molecules' C=O stretching vibration is the source of the peak location at 1730 cm^{-1} [80]. Following the delignification procedure, certain peak positions are removed and some peak positions with decreasing absorbance are left. Figure 4 displays the FTIR-ATR spectra of the DBW/rGO/PPy/PVA nanofiber composites. The DBW/rGO/PPy/PVA composite's FTIR-ATR spectrum analysis reveals peaks at 2907 cm^{-1} and 324 cm^{-1} , respectively that correspond to the carboxyl and hydroxyl groups and the OH tensile band. The stress of C=C bonds in the skeletal vibration of graphene nanosheets is indicated by the band at 1563 cm^{-1} [81][82]. The alkoxy (C-O) bending vibration groups situated at the edges of the GO nanosheets are the source of the peak at 1085 cm^{-1} . PVA's -CH₃ and -CH bending bands are visible at 1411 and 1324 cm^{-1} , respectively.

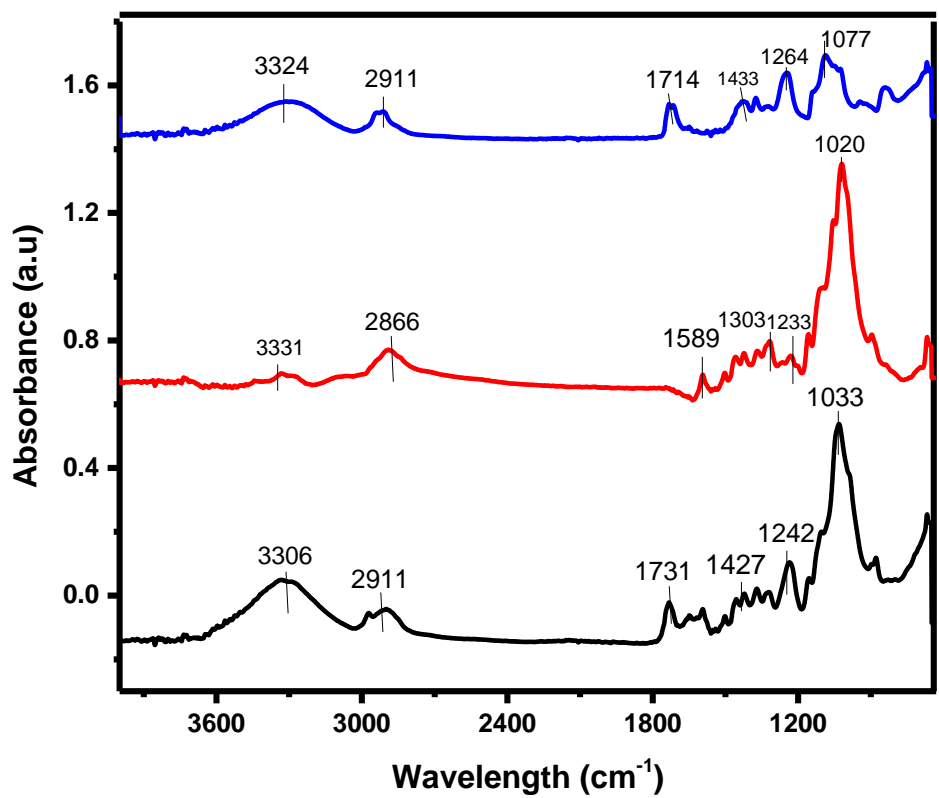


Fig. 3.3 FTIR spectrum of natural balsa wood, Delignified balsa wood and DBW@rGo@Ppy

Chapter 5 Conclusion

In this study, we demonstrated a clear and sustainable approach for the development of low-cost and eco-friendly hybrid electrodes for supercapacitors by using a green and 3D hierarchically porous template with open channels and high specific surface areas. In the past era, wood has been used by the mankind for different applications. It has been extensively utilized for many purposes, including housing, moving furniture, producing paper, making packaging, and more. Research on wood has changed as a result of improvements in characterization and processing methods. We had shown how to use the electrospinning technique to simply and readily produce an affordable, environmentally friendly solid-state supercapacitor. Flexible delignified balsa wood nanofibers (rGo/PPy) coated electrode was fabricated by electrospinning technique which was characterized by many techniques, such as FTIR-ATR, XRD, SEM-EDX, Raman shift and electrochemical analysis CV, GCD, EIS. The highest specific capacitance was obtained is 40F/g.

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