

**SYNTHESIS AND CHARACTERIZATION OF
POLYPYRROLE DOPED rGO/Ni-Sr FERRITES FOR
APPLICATIONS AS ELECTRODES IN ENERGY STORAGE
DEVICES**

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**in
Physics
By**

**Urvashi
Registration Number 42200075**

Supervised By

**Dr Vishal Sharma (13472)
Associate Professor and
Associate Dean**

**School of Chemical Engineering
and Physical Sciences**

Co-Supervised by

**Dr Alok Jain (12369)
Professor and
Associate Dean**

**School of Chemical Engineering
and Physical Sciences**



**LOVELY PROFESSIONAL UNIVERSITY,
PUNJAB
2026**

DECLARATION

I, hereby declared that the presented work in the thesis entitled“**Synthesis and characterization of polypyrrole doped rGO/Ni-Sr ferrites for applications as electrodes in energy storage devices**” in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of Dr.Vishal Sharma working as Associate Professor in the School of Chemical Engineering and Physical Sciences of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

Signature of Scholar

Name Urvashi

Registration Number 42200075

Date 07 May 2026

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled “**Synthesis and characterization of polypyrrole doped rGO/Ni-Sr ferrites for applications as electrodes in energy storage devices**” submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the School of Chemical Engineering and Physical Sciences, is a research work carried out by Urvashi (42200075), is bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

Signature of Supervisor

Name Dr Vishal Sharma

UID 13472

Date 07 May 2026

Signature of Co-Supervisor

Name Dr Alok Jain

UID 12369

Date 07 May 2026

ABSTRACT

Research into new electrode materials with improved electrochemical qualities has increased significantly as a result of the growing need for high-performance and efficient energy storage systems. Polypyrrole-doped reduced graphene oxide/Ni-Sr ferrite (PPy/rGO/Ni-SrFe₂O₄) nanocomposites were created and examined in this work to assess their possible use in energy storage devices such as supercapacitors. It is anticipated that the special combination of nickel-strontium ferrite (Ni-SrFe₂O₄), polypyrrole (PPy), and reduced graphene oxide (rGO) will provide high specific capacitance, electrochemical stability, and improved electrical conductivity due to the synergistic effects of the components. For energy storage systems to advance, new electrode materials with improved electrochemical qualities must be developed. In this work, a novel composite material was created by synthesizing polypyrrole (PPy) using chemical oxidative polymerization and doping it with Ni-Sr ferrites and reduced graphene oxide (rGO). High-quality graphene sheets with enhanced conductivity and surface area were guaranteed by the modified Hummers process used to create the rGO. Using the sol-gel auto-combustion process, Ni-Sr ferrites were created, yielding distinct nanostructures with adjustable electrical and magnetic characteristics.

The requirement for reliable energy storage has led to a quick search for materials with the best electrochemical properties. Despite having a higher power density than batteries, supercapacitors are nevertheless constrained by their finite energy density and capacity retention. Important fuel sources, including batteries, power devices, and internal combustion engines, work well as dependable low-power sources but are unable to recover energy or effectively handle large power demands due to their delayed release and re-energization. Due to the quick development of graphene-based supercapacitors, which will be a major advantage in cutting-edge electronic devices, devices with a certain amount of versatility are currently required. Numerous materials are being inspected to ensure they possess the proper attributes. Graphene is being investigated as a potential material for superconductors due to its unique properties,

including high conductivity and a large surface area. This work looked at metal/polymer doping, graphene-based superconductor types, and the oxides and reduced oxides of graphene-incorporated superconductors. We attempted to examine the researchers' approaches and determine which would be most ideal for achieving the best electrochemical performance by summarizing their findings. Several analytical methods were used to thoroughly characterize the produced PPy/rGO/Ni-Sr ferrite composite. The successful inclusion of the constituent phases was validated by X-ray diffraction (XRD) analysis, which also revealed phase purity and crystalline structures. The morphological characteristics were revealed by scanning electron microscopy (SEM), which showed that the ferrite nanoparticles were uniformly distributed throughout the graphene sheets and polymer matrix, improving surface area and structural stability. In order to confirm successful polymerization and doping contacts, Fourier-transform infrared spectroscopy (FTIR) was utilized to determine the chemical bonds and functional groups present in the composite. The Ni-Sr ferrite phase's successful development was confirmed by the XRD patterns, and the existence of polypyrrole and reduced graphene oxide in the composite structure was confirmed by FTIR spectroscopy. A well-distributed, linked nanostructure that facilitates quicker charge transfer and better ion diffusion was visible in FESEM pictures. It was found that polypyrrole was successfully doped and that the composite had various transition metal oxidation states, both of which increased redox activity. The study's findings demonstrate the potential of PPy/rGO/Ni-SrFe₂O₄ nanocomposites as promising electrode materials for supercapacitors of the future. They are appealing for real-world uses in energy storage systems due to their high specific capacitance, superior rate capability, and long-term cycle stability. With a focus on applications in energy storage devices, this work provides a simple, scalable approach for producing binary composites, especially for electrode materials. The composite (PPy/rGO/Ni-SrFe₂O₄) was made of Ni-SrFe₂O₄ metal oxide and the conductive polymer polypyrrole (PPy) via a sol-gel auto-combustion technique followed by chemical oxidative polymerization. For electrochemical testing, nickel foam served as the electrode substrate. The PPy/rGO/Ni-SrFe₂O₄ nanocomposites demonstrated excellent specific capacitance. The conducting polymer, graphene-based material, and ferrite nanoparticles all worked to provide improved electrochemical performance.

PPy was added to increase charge storage capacity, while rGO offered a highly conductive network that made electron movement easier. The energy storage efficiency was further increased by the addition of Ni-Sr ferrite nanoparticles, which further improved ion intercalation capability and redox activity. Additionally, a low charge transfer resistance was shown by the electrochemical impedance spectroscopy (EIS) measurement, demonstrating the composite's capacity to promote quick ion diffusion and electron transport. Using a 3M KOH electrolyte and nickel foam as a substrate, the electrochemical performance of the PPy/rGO/Ni-Sr ferrite composite was assessed using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). According to the findings, the composite demonstrated exceptional charge storage capacity and better capacitance retention, making it a viable option for supercapacitor applications. The electrical conductivity, ion diffusion, and charge storage mechanisms were all improved by the combined action of rGO and Ni-Sr ferrites, which raised the material's total energy storage efficiency. Furthermore, the ternary composite PPy/rGO/Ni-Sr ferrite electrode for energy storage applications was compared to the electrochemical characteristics of binary composites, rGO/Ni-Sr ferrite and PPy/Ni-Sr ferrite. To ensure consistency in preparation and characterization methods, the ternary composite was created utilizing the same procedures as the binary composite. The comparison analysis shed light on how each component affects conductivity, capacitance behavior, and charge storage. CV investigation showed the specific capacitance for binary composites rGO/Ni-SrFe₂O₄ was determined to be 516F/g, and the specific capacitance of PPy/Ni-SrFe₂O₄ was 654F/g at a scan rate of 10mV/s. However, ternary composite PPy/rGO/Ni-SrFe₂O₄ boosted this value to 710F/g. Galvanostatic charge-discharge (GCD) analysis also revealed that the binary composite's specific capacitance values for rGO/Ni-SrFe₂O₄ were 207 F/g at 1 A/g, and for PPy/Ni-SrFe₂O₄ binary composite, had a specific capacitance of 342F/g at 1A/g. Whereas the ternary composite's values were 517 F/g at 1 A/g. The study's findings demonstrate the PPy/NiSrFe₂O₄ composite's significant potential for producing high-performance electrodes that combine the benefits of PPy and NiSrFe₂O₄ for increased energy storage capacity. According to the findings, the composite demonstrated exceptional charge storage capacity, making it a viable option for supercapacitor applications. The electrical conductivity, ion diffusion, and charge

storage mechanisms were all improved by the combined action of rGO and Ni-Sr ferrites, which raised the material's total energy storage efficiency. High specific capacitance, low charge-transfer resistance, and extended stability across several charge-discharge cycles were all displayed by the improved composite. While rGO promoted charge transfer and enhanced the electrode material's overall conductivity, the presence of Ni-Sr ferrites aided in the electrochemical redox processes. The resulting hybrid material is a very appealing choice for energy storage applications because of its remarkable electrochemical properties. By clarifying the complementary effects of reduced graphene oxide, polypyrrole, and Ni-Sr ferrite in electrodes, this work aims to pave the way for the development of innovative materials with enhanced performance, broadening the range of possible energy storage applications.

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List of Abbreviations

Abbreviation	Full Form
PPy	Polypyrrole
GO	Graphene Oxide
rGO	Reduced Graphene Oxide
Ni-Sr	Nickel-Strontium
SCs	Supercapacitors
EDLC	Electric Double Layer Capacitors
PSc	Pseudocapacitors
Csp	Specific Capacitance
XRD	X-ray Diffraction
XPS	X-ray Photoelectron Spectroscopy
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
TMO	Transition Metal Oxides
LIBs	Lithium-Ion Batteries
SIBs	Sodium-Ion Batteries
RFBs	Redox Flow Batteries
CNTs	Carbon Nanotubes
CPs	Conducting Polymers
MWCNT	Multi-Walled Carbon Nanotube
CV	Cyclic Voltammetry
GCD	Galvanostatic Charge-Discharge
EIS	Electrochemical Impedance Spectroscopy
Me	Metal
Fe	Iron
Co	Cobalt
Mn	Manganese
Cu	Copper
Zn	Zinc

Abbreviation	Full Form
PFG	Polypyrrole/Fe ₂ O ₃ /rGO
PANI	Polyaniline
PEDOT	Poly(3,4-ethylenedioxythiophene)
AC	Alternating Current
PEMFCs	Proton Exchange Membrane Fuel Cells
SOFCs	Solid Oxide Fuel Cells
PC	Pseudo-capacitance
NCC	Nanocrystalline Cellulose
NF	Nickel Foam
AC-NF	Activated Carbon Nickel Foam
MCBP	Manganese ferrite/carbon black/polyaniline
MG	Manganese ferrite microspheres
VCM	Vacuum centrifuge mixing
LNSRG	Lanthanum-doped Nickel-tin oxide/reduced graphene oxide
ASC	Asymmetric Supercapacitors
SRGO	Sonochemically Reduced Graphene Oxide
DI	Deionized Water
CTAB	Cetyltrimethylammonium Bromide
PVDF	Polyvinylidene Fluoride
NMP	N-Methyl Pyrrolidone
R _{ct}	Charge Transfer Resistance
R _s	Solution Resistance
Z _w	Warburg Impedance

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Chapter 1

Introduction

1.1 Motivation

Fossil fuel sources are being depleted, and the biosphere is facing serious ecological harm as a result of the ongoing increase in global greenhouse gas emissions. With the ever-increasing demand for energy solutions that are efficient, dependable, and environmentally friendly, energy storage devices have become an essential component of modern technology. The development of improved energy storage technologies has become more important than it has ever before as a result of worries about the environment and rising energy consumption. Energy storage solutions that are environmentally friendly, cost-effective, and highly efficient are in great demand as a result of the growing worries about the environment and the changing requirements of modern civilization. The development of sustainable energy systems that are sustainable is becoming more dependent on the utilization of energy storage devices in this context. Addressing the obstacles that are associated with energy storage is one of the most serious topics that the twenty-first century has to offer. In response to the growing need for high-performance energy storage devices, a significant amount of research has been conducted into the development of innovative electrode materials that possess superior electrochemical capabilities. This need places an emphasis on the requirement for modern energy storage systems that are capable of integrating with sustainable energy technologies in an effective manner, as well as clean, renewable energy sources. Batteries, fuel cells, and supercapacitors are some of the electrochemical energy production and storage systems that are utilized the most frequently. There are various benefits and drawbacks associated with each of these technologies. The charge-discharge rates of batteries are slower, and their cycle life is shorter. Due to their remarkably quick charge-discharge capabilities and long operational lifespan, supercapacitors have garnered a substantial amount of attention among the various other technologies for energy storage. Because supercapacitors store energy electrostatically, as opposed to ordinary batteries, which rely on chemical reactions for energy storage, they are able to charge and discharge at a considerably faster rate. Applications that require rapid bursts of energy, such as electric vehicles, portable electronics, and

renewable energy systems, are ideal candidates for supercapacitors due to their one-of-a-kind mechanism. Fuel cells provide a constant supply of energy, but they require a reliable source of fuel and need to be supported by a sophisticated infrastructure. The capacity of supercapacitors, on the other hand, to give high power output, rapid energy delivery, and extended cycle life makes them one of the most promising sustainable technologies for energy conversion and storage. They bridge the gap between conventional capacitors and batteries using their ability to store energy[1-3]. Supercapacitors' quick charging and discharging speeds, incredibly long lifespan, simple design, and environmental friendliness make them a great supplement to or alternative to batteries. This is why supercapacitors are becoming increasingly popular. Supercapacitors are ideally suited for use in grid energy storage, electric vehicles, and industrial power management due to the properties described above. Choosing the appropriate electrode materials is one of the most important aspects that determines how well supercapacitors operate. Overcoming the limits that now exist and improving the overall efficiency of the device requires the development of improved electrode materials that possess superior electrochemical characteristics. Charge transport mechanisms that are efficient, have chemical stability, a vast surface area, and great electrical conductivity are all characteristics that must be present in high-performance electrodes. As a result of their high surface area and electrical conductivity, traditional carbon-based materials, such as activated carbon and graphene, have been utilized extensively for the electrodes of supercapacitors. Scientists are now investigating innovative nanocomposites that blend carbon materials with metal oxides, conducting polymers, and transition metal ferrites. This is being done in order to further increase performance [4-8]. Conductivity, electrochemical stability, and energy storage capacity are all improved in nanocomposites, which are substances that incorporate numerous functional components at the nanoscale. Examples of metal oxides that exhibit excellent pseudocapacitive behavior are nickel oxide, cobalt oxide, and iron oxide. These metal oxides contribute to improved charge storage through reactive redox reactions that can be reversed. These nanocomposites offer greater energy storage capabilities when paired with conductive materials such as graphene or reduced graphene oxide (rGO). Providing extra charge storage sites and boosting the overall capacitance of electrode materials are two of the most important roles that conducting polymers, such as polypyrrole (PPy) and polyaniline (PANI), play in bettering the performance of

supercapacitors. Researchers have been given a new viewpoint on energy storage mechanisms and material design thanks to the arrival of supercapacitors, which belong to a new category of energy storage devices. Supercapacitors with better energy densities, faster charge-discharge cycles, and longer operational lifespans have been developed as a result of the integration of new materials and nanostructures, which have led to substantial advancements in the sector. In order to realize the full potential of supercapacitors for future energy storage applications, it will be necessary to optimize electrode materials, electrolyte compositions, and device topologies. This will be the case as research proceeds. Supercapacitors, in conclusion, show a great deal of potential as a sustainable energy storage solution, which can be used in conjunction with the technologies that are already in place, such as fuel cells and batteries. Supercapacitors operate by effectively separating charges at the electrode- electrolyte interface to facilitate energy storage. These are commonly known as electric double-layer capacitors . As a result, the devices can now store and release energy at a faster rate compared to their previous capabilities with batteries. Supercapacitors exhibit minimal internal resistance and possess an exceptionally high capacity. Pseudocapacitors (PCs) generally exhibit greater specific capacitance and energy density compared to electric double-layer capacitors made from carbonaceous materials. The formation of a double layer on the electrode surface of EDLCs results in ion adsorption, which facilitates the storage of electrostatic charge. Ongoing research efforts, however, need to be directed toward the development of new electrode materials that have enhanced electrochemical characteristics to fully exploit their potential. The next generation of supercapacitors has the potential to overcome the constraints that are currently in place and contribute to a future that is more environmentally friendly and cost-effective in terms of energy consumption[9-11].

1.2 Types of Electrochemical Energy Storage Devices and Their Mechanisms

Electrochemical energy storage devices play a crucial role in modern energy technologies by efficiently storing and releasing energy for a variety of applications. These devices function through different energy storage mechanisms, which primarily include electrochemical reactions, charge separation, and ion intercalation. Below are the major types of electrochemical energy storage devices and their mechanisms:

1.2.1 Batteries

- i. **Lithium-ion Batteries (LIBs):** The operation is based on the intercalation and deintercalation of lithium ions between the materials of the anode and the cathode, which enables great energy density and efficiency.
- ii. **Lead-acid Batteries:** Energy can be stored and released by the utilization of a reaction that is reversible and involves lead dioxide, sponge lead, and sulfuric acid.
- iii. **Sodium-ion Batteries (SIBs):** Function similarly to LIBs but utilize sodium ions, making them a cost-effective alternative.
- iv. **Flow Batteries:** Store energy in liquid electrolytes containing redox-active species that circulate between external reservoirs and electrodes.

1.2.2 Supercapacitors: Store charge electrostatically at the electrode- electrolyte interface. Supercapacitors can be further classified into:

- i. **Electric Double Layer Capacitors (EDLCs):** Utilize the physical separation of charge at the electrode-electrolyte interface, typically using carbon-based materials such as activated carbon or graphene.
- ii. **Pseudocapacitors:** Store charge through fast and reversible redox reactions occurring at the surface or near-surface of the electrode materials, such as conducting polymers or transition metal oxides.
- iii. **Hybrid Supercapacitors:** Combine characteristics of both EDLCs and pseudocapacitors to achieve higher energy density and better cycle stability, often incorporating nanocomposites or hybrid electrode materials. Hybrid supercapacitors have gained significant attention due to their ability to bridge the gap between electric double-layer capacitors (EDLCs) and pseudocapacitors. By incorporating features of both storage mechanisms, hybrid supercapacitors exhibit superior electrochemical performance, enhanced energy density, and improved cycling stability. The combination of EDLC-like and pseudocapacitive behavior allows hybrid supercapacitors to achieve high capacitance and greater energy efficiency compared to traditional supercapacitors.

1.2.3 Fuel Cells

- v. **Proton Exchange Membrane Fuel Cells (PEMFCs):** Generate

electricity by electrochemically combining hydrogen and oxygen, producing only water as a byproduct.

- vi. **Solid Oxide Fuel Cells (SOFCs):** Operate at high temperatures and use solid ceramic electrolytes to facilitate ion transport and efficient energy conversion.

1.2.4 Redox Flow Batteries (RFBs)

Store energy in liquid electrolytes containing electroactive species that undergo redox reactions, offering scalability and long cycle life.

1.2.5 Metal-Air Batteries

Use oxygen from the air as a cathode reactant, which greatly increases energy density compared to regular batteries. Each of these energy storage devices has its own benefits and uses. Researchers are always working to make them more efficient, longer-lasting, and environmentally friendly. New electrode materials, electrolytes, and battery designs are still pushing the development of electrochemical energy storage technologies for large-scale energy storage, portable electronics, and electric cars[12- 17]

1.3 Mechanisms for the storage of energy in supercapacitors

The electrochemical energy storage technology known as supercapacitors has a long lifespan, a high charging/discharging rate, and a tremendous power density. Three categories of supercapacitors can be distinguished by their charge mechanisms and electrode active materials: (i) Electrical double-layer capacitors (EDLC), (ii) hybrid capacitors, and (iii) pseudocapacitors. Ion adsorption at the interface between the electrode surface and the electrolyte creates a double layer that permits charge accumulation without the need for redox reactions, which is the mechanism underlying electrostatic charge storage in electric double-layer capacitors .EDLCs are very effective for high-power energy storage applications because of this mechanism, which enables quick cycles of charging and discharging.

The mechanism by which supercapacitors can store energy is explicable in terms of three different capacitive actions:

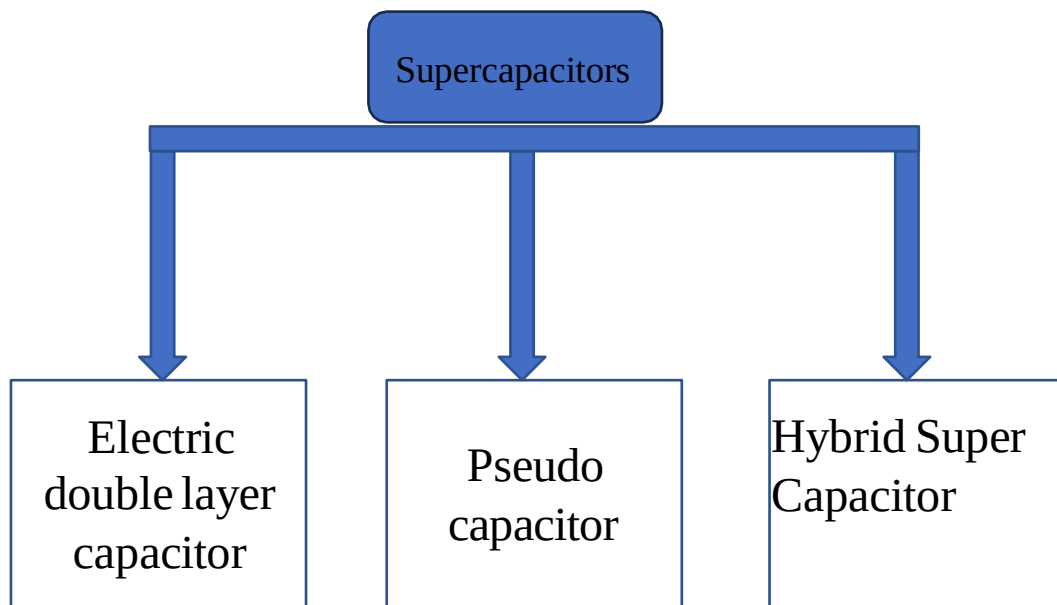


Fig 1.2.1 Types of Supercapacitors

- (1) EDLC(Electrochemical double-layer capacitors) employ the pure electric charge that builds up at the electrode contact
- (2) PC(Pseudo-capacitance)is produced byrapid and reversible surface redox reactions
- (3) Hybrid Capacitors, in which both methods are utilized.

1.3.1 Mechanism of EDLC Supercapacitors

- Rather than using electrochemical reactions, EDLCs use electrostatic charge separation.
- Ions from the electrolyte move toward the electrode surfaces that are oppositely charged when a voltage is applied, creating a double layer at the interface. The surface area of the electrode material and the accessibility of electrolyte ions determine how much energy is stored. EDLCs have good cycle stability and quick charge-discharge rates since faradaic (charge transfer) processes do not occur.
- Because of their great surface area and superior conductivity, carbon-based materials such as graphene and activated carbon are frequently utilized for EDLC electrodes.
- Ion adsorption causes charge accumulation at the interface without material deterioration, according to the Helmholtz double-layer model, which describes the energy storage capacity of EDLCs.

•By optimizing electrode porosity, electrolyte selection, and surface modification procedures, EDLCs' capacitance and energy density can be raised.

1.3.2 Mechanism of Pseudocapacitors

- Pseudocapacitors store energy through faradaic charge transfer involving fast and reversible redox reactions.
- The electrochemical storage mechanism is based on surface or near-surface reactions, allowing high capacitance compared to EDLCs.
- Materials such as conducting polymers and transition metal oxides serve as active components due to their redox-active nature.
- The charge storage occurs via adsorption/desorption of ions onto the electrode surface.
- Unlike EDLCs, pseudocapacitors involve electron transfer between electrolyte species and the electrode, contributing to higher specific capacitance.
- Pseudocapacitors can achieve energy densities higher than EDLCs while maintaining rapid charge/discharge characteristics.
- The performance of pseudocapacitors is influenced by factors such as electrode material composition, electrolyte selection, and structural morphology of active materials.

1.3.3 Mechanism of Hybrid Supercapacitors

Hybrid supercapacitors operate on a dual charge storage mechanism that combines electrostatic charge accumulation from EDLCs with faradaic redox reactions from pseudocapacitors. This dual mechanism enables them to deliver higher energy density than EDLCs while maintaining superior power density compared to conventional batteries.

Electric Double Layer Capacitance (EDLC) Contribution:

- In hybrid supercapacitors, one of the electrodes, typically made from carbon-based materials (e.g., graphene, activated carbon, or carbon nanotubes), functions as an EDLC.
- Charge storage occurs due to the electrostatic accumulation of ions at the electrode-electrolyte interface.
- This mechanism ensures rapid charge-discharge rates and excellent cycle stability due to the absence of faradaic reactions.

B) Faradaic Redox Reactions Contribution:

- The second electrode is typically composed of a pseudocapacitive material, such as conducting polymers or transition metal oxides.
- These materials undergo fast and reversible redox reactions at the electrode surface, contributing additional charge storage capacity.
- The involvement of redox reactions enhances the overall capacitance and energy density of hybrid supercapacitors.

C) Ion Diffusion and Charge Transfer Mechanism:

- The electrolyte plays a crucial role in facilitating ion movement between the two electrodes.
- The balance between electrostatic charge storage and faradaic reactions is optimized by selecting suitable electrolyte compositions and electrode materials.
- The ion transport and charge storage mechanisms are highly dependent on the porosity, surface area, and conductivity of the electrode materials.

1.4 Advantages of Hybrid Supercapacitors:

- Higher energy density compared to EDLCs due to the inclusion of faradaic charge storage.
- Superior power density compared to batteries, ensuring fast charge-discharge cycles.
- Extended cycle life due to stable electrochemical reactions and high reversibility.

Versatile applications in automotive, consumer electronics, and industrial power management.

Hybrid supercapacitors continue to be a focal point of research, with ongoing advancements in material synthesis, electrode design, and electrolyte optimization. By fine-tuning these parameters, future hybrid supercapacitors are expected to achieve even greater efficiency, making them a key technology in sustainable energy storage solutions. Many people are interested in supercapacitors due to their low-cost electrode materials. In order to create hybrid supercapacitors that strike the ideal balance between power density, energy density, and cycling stability, making them extremely promising for next-generation energy storage applications, researchers are integrating electrostatic and pseudocapacitive charge storage methods. An electrolyte, cathode, anode

electrodes, and a separator are some of the essential parts of a supercapacitor, which cooperate to provide effective energy delivery and charge storage. Since the electrodes are the main locations for charge accumulation and electrochemical processes, they have a significant impact on the supercapacitor's overall performance, energy density, and cycle stability. The manufacturing process has a significant impact on the electrodes' mechanical stability, surface area, and pore size distribution, among other structural characteristics. Ion diffusion paths, charge transfer resistance, and overall energy storage efficiency can all be improved by using nanostructured materials, hierarchical structures, and composite electrode designs. The long-term cycling stability and longevity of the supercapacitor are further influenced by variables such as coating thickness, homogeneity, binder selection, and electrode composition. In order to achieve high-performance energy storage applications, defect-free, high-conductivity electrodes must be formed using optimized fabrication techniques. The objective is to develop an electrode that has a more specific surface area and superior electrochemical properties that can store a large amount of electrical energy with extended cycle efficiency in order to meet the present energy storage demands. Electrodes can be made from a variety of materials, both metallic and nonmetallic, that exhibit modest electrical conductivity. Their morphology can also be altered in order to improve supercapacitor performance. Adding two materials to a single electrode can also enhance the performance of a supercapacitor. Different electrode materials produced using various processes have distinctive structures and properties, which lead to inconsistent supercapacitor behavior. Advanced materials that have excellent qualities as electrodes for supercapacitor applications include metallic oxides, conducting polymers, ferrite, and metal hydroxide. To get beyond the limitations of the base electro-active material, binary and ternary nanocomposites have recently been the subject of extensive research. Carbonaceous materials, transition metal oxides and conductive polymers are commonly employed in the structure of supercapacitor electrodes. In many cases, combining these materials resulted in electrodes with high capacitance. Carbon-based materials, which have a large surface area, good electrical conductivity, and great chemical stability, make up the majority of EDLCs. Graphene, carbon nanotubes and activated carbon are some of the most popular materials utilized in EDLC electrodes; each offers special structural and electrochemical benefits. While CNTs improve charge transport capabilities because of their distinctive tubular nanostructure, graphene offers

an ultrathin, highly conductive surface with remarkable mechanical strength. The enormous specific surface area and well-developed porosity of activated carbon, on the other hand, make it a preferred material for ion adsorption and storage within the double layer. Pseudocapacitors, as opposed to EDLCs, function by use of quick and reversible faradic reactions that take place at the surface of the electrode material. Through charge transfer processes, these reactions greatly increase specific capacitance and energy storage capacity above and beyond what is possible with only electrostatic mechanisms. Surface redox processes, which preserve quick charge-discharge properties while offering a larger charge storage density, are the basis of the pseudocapacitive mechanism. Conductive polymers, metal hydroxides, and metal oxides are examples of common pseudocapacitive materials that have quick redox kinetics and strong electrochemical activity. Because of their flexibility, high conductivity, and lightweight nature, conductive polymers, including polypyrrole (PPy), polyaniline (PANI), and poly(3,4-ethylenedioxythiophene)(PEDOT), are appealing for flexible supercapacitors. Furthermore, metal oxides are being researched in great detail due to their high redox activity and exceptional electrochemical stability, which enhances hybrid supercapacitors' ability to store energy [19-23].

While conducting polymers (CPs) and metal oxides are used as electrode materials in pseudocapacitors, high surface area carbon-based materials are usually used in EDLC. Among the several CPs, polypyrrole (PPy) is the most effective electrode material for pseudocapacitors. However, PPy's commercial application is limited due to its low thermal stability and weak electrical conductivity. Despite being considered a promising material for supercapacitors, polypyrrole's rapid deterioration during charge and discharge severely limits its capacitive performance. In order to overcome this issue, PPy is commonly mixed with carbon-based materials to form PPy/carbon-based nanocomposites, which are utilized as active materials in supercapacitors. Researchers are particularly interested in carbon-based materials, particularly rGO, multi-walled carbon nanotubes (MWCNT), and nanocrystalline cellulose (NCC). The rGO stands for MWCNT because of its remarkable mechanical strength, NCC because of its environmental friendliness, and out because of its outstanding electrical conductivity. Because of their enrichment properties, nanocomposites have a wide range of applications as active materials for supercapacitors. Many studies on PPy/rGO nanocomposites, for example, demonstrate their good electrochemical performance.

Furthermore, it was mentioned that the electrical and thermal stability of CPs might be considerably improved by the addition of graphene nanosheets. A promising synergistic effect between graphene and polypyrrole has been shown to improve the supercapacitive behavior of transition metal hydroxides and oxides. Among the various conducting polymers, PPy is thought to be one of the most active materials because of its easy synthesis process, affordability, environmental friendliness, acceptable thermal stability, and increased energy density. However, adding Gr enhances PPy's qualities due to its large specific surface area, great electrical conductivity, and remarkable mechanical strength. Numerous efforts have been made to improve the energy density of hybrid supercapacitors, including the development of linked nanoparticles, coupling nanoparticles with conducting polymers, coupling nanoparticles with carbon nanotubes, and scaffolding nanoparticles on rGO sheets. Nanocomposites based on reduced graphene oxide (the physical analog of graphene) garnered the greatest attention due to their large specific surface area and improved electrical conductivity. Additionally, by stopping scaffolded nanoparticles from aggregating during electrochemical performance, the rGO sheet raises the specific surface area. RuO_2 , MnO_2 , NiFe_2O_4 , NiO , NiCo_2O_4 , and other transition-metal oxide nanoparticles have been described as pseudo-capacitor electrode materials. Furthermore, because the contributions from A, B, and Fe ions provide richer redox reactions than monometallic ferrites, ferrite-based nanoparticles based on binary transition metals, such as ABFe_2O_4 (where A and B are combinations of Mn, Cu, Ni, Co, Sr, etc.), are expected to show improved supercapacitance behavior. If the specific capacitance and electrical conductivity of a transition metal oxide are low, its specific capacitance and conductivity can be increased. The extraordinary improvement in the electrochemical performance of binary transition metal oxide nanoparticles, such as Ni/Mn oxide, Ni/Co oxide, Mn/Fe oxide, etc., has attracted greater interest due to their ability to display different redox states.

Metal oxides and conducting polymers can generate significantly more energy densities through Faradic reactions than EDLC-based supercapacitors, while having less cycle stability and power density. In order to create supercapacitors with incredibly high capacitances, we present here a straightforward and scalable synthetic method for creating ternary composite materials as electrode materials [24-37].

1.5 Ferrites as Efficient Electrode

Ferrites, also known as magnetic oxides, have a long history and have been used for many years. Ferrites can be treated as potential electrodes for energy storage. These materials possess unique electrical and magnetic properties, making them highly attractive for energy storage applications, particularly in supercapacitors and battery electrodes. Ferrites exhibit excellent chemical stability, good electrical conductivity, and high surface area, all of which contribute to enhanced charge storage capability. With the increasing global demand for efficient and sustainable energy storage solutions, research has focused on optimizing ferrite-based materials for electrochemical applications. Their ability to undergo redox reactions and facilitate charge transfer mechanisms has made them viable alternatives to conventional electrode materials. Moreover, the tunability of their structural and electronic properties enables enhanced performance in electrochemical energy storage devices. Ferrites can be made into powder or thin films using a variety of techniques, including high-temperature solid-state reaction, sol-gel, coprecipitation, pulsed laser deposition, high-energy ball milling, and hydrothermal. Pressing a blend of powders comprising the component raw ingredients to the desired shape creates a ferrite core, which is subsequently sintered into a ceramic component. Ferrites' range of uses in electrical circuitry is continually expanding. Ferrite components are the preferred option for both traditional and novel applications due to their broad variety of potential geometries, ongoing advancements in material properties, and relative affordability [38-41].

1.5.1 Uses of Ferrites in Energy Storage Devices

Ferrites have been extensively studied and employed in various energy storage applications due to their versatile electrochemical properties. Some key uses include:

i) Supercapacitor Electrodes:

- Ferrites serve as efficient electrode materials for supercapacitors due to their ability to undergo rapid redox reactions.
- Their high surface area and porous nature facilitate effective charge accumulation and ion diffusion.
- The incorporation of ferrites with conductive materials such as graphene enhances their electrochemical performance.

ii) Battery Electrodes:

- Ferrites are used in lithium-ion and sodium-ion batteries as anode and cathode materials.
- Their ability to store charge through faradaic processes contributes to higher energy densities.
- Advanced ferrite-based nanocomposites have been developed to improve battery cycle life and efficiency.

ii) Hybrid Energy Storage Systems:

- Ferrites are often integrated into hybrid systems, combining the advantages of batteries and supercapacitors.

The combination of ferrites with conducting polymers or carbon-based materials results in enhanced charge storage and cycling stability.

By leveraging their unique electrochemical properties, ferrites have the potential to significantly improve the performance of next-generation energy storage devices. Future research should focus on optimizing their synthesis, exploring novel dopants, and developing scalable fabrication methods to facilitate their commercial adoption[44-47].

1.5.2 Nickel Ferrite

The well-known spinel ferrite material nickel ferrite (NiFe_2O_4) has attracted a lot of interest due to its electrochemical characteristics and possible uses in energy storage systems. Nickel ferrite is an effective electrode material in supercapacitors and battery applications because of its stable crystal structure, excellent electrical conductivity, and exceptional electrochemical performance. Ni^{2+} and Fe^{3+} ions are dispersed in octahedral and tetrahedral locations within the lattice of nickel ferrite's cubic spinel structure. Its inherent electrical conductivity, redox activity, and effective charge storage are all influenced by this configuration. The substance is appropriate for long-term energy storage applications due to its well-known chemical stability and resistance to corrosion.

- Nickel ferrite exhibits excellent pseudocapacitive behavior due to its ability to undergo fast and reversible redox reactions.
- The integration of nickel ferrite with carbon-based materials such as graphene enhances its conductivity and overall electrochemical performance.
- NiFe_2O_4 -based supercapacitors exhibit high specific capacitance, low charge- transfer resistance, and long cycle life.[48-49].

Advantages of Nickel Ferrite Electrodes

1. **High Redox Activity:** NiFe_2O_4 undergoes multiple oxidation and reduction reactions, enhancing its energy storage capacity.
2. **Stable Structure:** The spinel structure of nickel ferrite ensures high structural stability and resistance to degradation.
3. **Enhanced Conductivity:** Ferrite exhibits improved electron transport.
4. **Cost-Effectiveness:** Nickel ferrite is abundant and inexpensive compared to other electrode materials, making it an economically viable choice.[50-51]

1.5.3 Strontium Ferrite

Because of its superior electrochemical qualities, stable structure, and strong redox activity, SrFe_2O_4 is a potential electrode material for energy storage applications. SrFe_2O_4 with special ionic and electrical characteristics that make it ideal for batteries and supercapacitors. SrFe_2O_4 is a desirable choice for high-performance energy storage devices because of its capacity to undergo reversible redox reactions, which improves its charge storage capacity. The layered structure of strontium ferrite facilitates efficient electron and ion transport, which is essential for its electrochemical uses. Strontium stabilizes the material and increases its overall conductivity when it is present in the lattice. Strong magnetic characteristics are another feature of SrFe_2O_4 that could be helpful in multipurpose energy storage devices. Because of its exceptional cycle stability, high capacitance, and great electrochemical performance, strontium ferrite is frequently used in energy storage devices. It has been studied both alone and in combination with other conducting materials as an electrode material.

- SrFe_2O_4 displays excellent pseudocapacitive properties, enabling it to store charge through faradaic reactions.
- Its high surface area and layered structure facilitate rapid ion diffusion and charge transfer.
- When combined with graphene or conductive polymers, SrFe_2O_4 -based supercapacitors demonstrate enhanced energy storage efficiency and improved electrochemical stability [52,53].

Advantages of SrFe_2O_4 Electrodes

1. **High Redox Activity:** The transition metal ions in SrFe_2O_4 contribute to efficient faradaic charge storage mechanisms.

2. **Chemical and Structural Stability:** SrFe_2O_4 exhibits excellent stability, reducing material degradation over time.
3. **Improved Ion Diffusion:** The layered structure of SrFe_2O_4 enhances ion transport, leading to higher charge storage efficiency.
4. **Low Cost and Abundance:** Strontium ferrite is composed of inexpensive and widely available elements, making it a cost-effective choice for energy storage applications[54].

1.5.4 Nickel-Strontium Ferrite

A type of spinel ferrite material known as Nickel-Strontium ferrite (Ni-Sr ferrite) has exceptional electrical, magnetic, and electrochemical qualities. Their distinct qualities have drawn a lot of interest for a range of technical uses, such as electromagnetic shielding, energy storage devices, and catalysis. Ni-Sr ferrites are ideal options for supercapacitor electrodes and battery materials because of their high saturation magnetization, low coercivity, and strong electrical conductivity.

i) Structural and Magnetic Properties

Nickel and strontium ions are dispersed across the lattice at octahedral and tetrahedral locations in Ni-Sr ferrites, which form in a cubic spinel structure. Lattice distortions brought about by the presence of Sr ions affect the material's electrical and magnetic characteristics. The synthesis process, dopant concentration, and annealing temperatures all affect how magnetically Ni-Sr ferrites behave.

ii) Electrochemical Performance in Energy Storage Devices

Ni-Sr ferrites are used in energy storage applications due to their ability to undergo reversible redox reactions, which contribute to enhanced charge storage capabilities. Their high surface area, combined with excellent electrical conductivity, ensures efficient ion transport and charge storage in supercapacitors and batteries.

iii) Supercapacitor Applications

- Ni-Sr ferrites exhibit superior pseudocapacitive behavior, enabling them to store charge through faradaic reactions.
- The integration of Ni-Sr ferrites with conductive materials such as graphene or polypyrrole enhances their charge storage efficiency.

- Supercapacitors based on Ni-Sr ferrite electrodes display high power density and improved cycling stability[55,56].

Supercapacitors initially utilized carbon-based materials because of their extensive surface area. Metal oxides exhibit high specific capacitance and low resistance, facilitating the development of supercapacitors with elevated energy and power densities. The study of conducting polymers in pseudocapacitors has garnered significant attention in recent years due to their impressive specific capacitance, attained through reversible redox reactions. Polypyrrole has shown remarkably high conductivity along with impressive mechanical and environmental durability. Recently, composites consisting of polymers and carbon-based nanofillers have been utilized as electrodes, demonstrating a significant synergistic effect in enhancing supercapacitor performance.

Polymers that can conduct electricity, especially polypyrrole (PPy), have garnered significant interest as materials for electrodes because of their impressive conductivity, outstanding electrochemical properties, and straightforward synthesis process. Nonetheless, the fundamental structural deterioration and constrained mechanical stability of PPy limit its practical uses. In response to these challenges, the integration of nanocomposites like reduced graphene oxide rGO and metal ferrites has been investigated to improve the stability and conductivity of PPy-based electrodes. PPy, a type of conducting polymer, has attracted significant interest because of its impressive electrical conductivity, straightforward synthesis process, and pseudo-capacitive characteristics. Nonetheless, enhancements in mechanical stability and cycling durability are essential for their viability in long-term applications. An effective strategy to address these limitations involves the integration of nanostructured carbon-based materials, particularly reduced graphene oxide (rGO). rGO offers a high surface area, excellent electrical conductivity, and robust mechanical strength, positioning it as an optimal matrix for hybrid electrode materials. The current investigation reveals that Nickel ferrite, when doped with Strontium (Sr) and possessing a spinel structure, demonstrates enhanced electrochemical characteristics[57-59].

1.6 Supercapacitors Based on Graphene

There is a lot of potential for graphene-based supercapacitors with different arrangements to be used for storing energy. Several important factors affect the choice of electrode materials for supercapacitor applications. These include a large surface

area, controlled pore size to make it easier for electrolyte ions to get to the electrodes, good electrical conductivity, and strong mechanical strength to keep the structure intact when it is bent. The structure has always included conductive adhesives, binders, and electrodes. People often use conductive metals to make electrodes. The problem with the models that were used before was that they made the devices too heavy. Graphene was chosen to help with this big problem because it is light and has a large operational area ($2630 \text{ m}^2 \text{ g}^{-1}$). Even so, graphene showed promising electrochemical properties. The strong Van der Waals attraction between atoms and the single-plane π - π bond attraction make them likely to restack, which is a big problem. Different types of substrates have been used in different situations to deal with the problem. The solution to this problem is to add different materials, such as metals, non-metals, and polymers, to graphene to make it stronger. Graphene-based supercapacitors are used in a wide range of fields because they are so flexible. The intrinsic electronic double-layer capacitor has a capacitance of 21 mFcm^{-2} . Using the whole surface area gives this material a specific capacitance of 550 Fg^{-1} , which is the highest ever recorded for a carbon material. Adding oxygen-rich groups to electrodes makes them more conductive. This is a big benefit of using different types of graphene, such as graphene oxides and reduced graphene oxides [24-26].

1.6.1 Performance of a reduced graphene oxide-based supercapacitor

Reduced graphene oxide (rGO) has surfaced as a highly promising electrode material for supercapacitors, attributed to its remarkable electrical conductivity, extensive surface area, and outstanding mechanical strength. The distinctive two-dimensional configuration of rGO promotes improved charge storage capacity by enabling effective ion transport and swift electron mobility. In contrast to pristine graphene, rGO features residual oxygen functional groups that enhance the number of electrochemically active sites, thereby boosting the overall performance of supercapacitors.

i)Electrochemical Characteristics

Supercapacitors based on rGO electrodes exhibit remarkable electrochemical properties, including high specific capacitance, low internal resistance, and excellent rate capability. When tested using CV, rGO-based supercapacitors show nearly rectangular CV curves, indicating ideal electric double-layer capacitor behavior. The charge-discharge profiles obtained from GCD measurements confirm the high -power density and rapid energy storage capability of rGO electrodes.

EIS measurements reveal that rGO-based supercapacitors have minimal charge transfer resistance, ensuring efficient charge- discharge processes. The presence of interconnected pores and high conductivity of rGO further enhances electrolyte penetration, optimizing ion diffusion at the electrode- electrolyte interface

ii) Synergistic Effects of rGO Composites

To improve the performance of rGO-based supercapacitors, hybrid composites that integrate rGO with conductive polymers or metal oxides have been created. For example, the integration of PPy with rGO enhances charge storage capabilities owing to the pseudocapacitive characteristics of PPy. In a similar vein, incorporating metal oxides like MnO₂ or NiO improves the redox reaction efficiency, resulting in increased energy density and extended cycling stability.

iii) Stability and Cycling Performance

A significant benefit of rGO-based supercapacitors is their impressive long-term cycling stability. Unlike regular battery electrodes, which lose their properties after many cycles, rGO keeps its electrochemical properties even after thousands of charge-discharge cycles. Research shows that after 5000 cycles, rGO electrodes still have more than 90% of their original capacitance. This shows that they are very durable and can be used for long-term energy storage.

The strong structure and high flexibility of rGO supercapacitors make them stable. The strong carbon structure stops the electrodes from breaking down, which keeps them working well through many electrochemical cycles. Also, because rGO is resistant to oxidation, it is less likely to cause unwanted side reactions, which makes the device last longer. There are many ways to show how rGO sheets can be used instead of graphene sheets. The rGO sheets are flexible and very good at conducting electricity. They act as a good pathway for the released electrons and a supportive base to reduce internal stress. The interface between two graphitic areas can trap charge carriers, and the zone with more oxygen has very high resistance. There are many ways to make rGO films that stand on their own. One way to stop graphene from restacking is to make a precise three-dimensional network out of graphene layers. However, the fact that electrolyte ions can't move freely through the internal pores is still a big problem. Putting pseudocapacitive compounds on surface-functionalized graphene is another way to do it. These materials not only act as a physical barrier to keep things from stacking, but they also

increase energy densities by adding multiple-fold capacitance through surface redox processes. Also, combining graphene with pseudocapacitive materials could lead to the development of flexible, lightweight electrodes with high specific capacitance and strong mechanical properties. So, it is important to make new pseudocapacitive materials that are cheap, easy to find, and have a lot of redox activity. In this context, metal oxides have become very popular among academics. Ruthenium oxide has the highest capacitance of all metal oxides, but it can't be used as much because it's expensive and toxic. A lot of cheap oxides that are easy to find on Earth have been studied. For example, cubic, spinel-type ferrites AFe_2O_4 (where A stands for Mn, Co, Ni, Cu, Sr, Zn) show promise as pseudocapacitors[59-61].

1.6.2 Benefit of Polypyrrole Conducting Polymer and rGO Doping with Metal Ferrite

The development of high-performance electrodes is essential for the progress of energy storage devices, especially supercapacitors and batteries. PPy and oxide rGO have been extensively studied as effective electrode materials because of their remarkable electrical conductivity, electrochemical stability, and capacity to improve charge storage mechanisms. When infused with metal ferrites, these materials demonstrate enhanced energy storage capabilities, positioning them as optimal candidates for advanced energy storage applications.

Advantages of Polypyrrole (PPy) in Electrode Fabrication Polypyrrole stands out as a highly examined conducting polymer, recognized for its impressive electrical conductivity, favorable mechanical properties, and straightforward synthesis process. The distinctive conjugated structure facilitates swift charge transport, rendering it a highly effective material for electrodes in supercapacitors and batteries.

i) High Conductivity and Charge Storage

- PPy has a high degree of conjugation, enabling efficient electron transfer and enhancing charge storage.
- The presence of nitrogen atoms in the polymer backbone improves ion diffusion and enhances redox activity, contributing to higher specific capacitance.

ii) Electrochemical Stability

- PPy exhibits good cyclic stability, maintaining its electrochemical performance over multiple charge-discharge cycles.
- The polymer structure provides flexibility, preventing electrode degradation and ensuring long-term durability.

iii) Synergistic Effect with Metal Ferrites

- The combination of PPy with metal ferrites such as NiFe_2O_4 and SrFe_2O_4 enhances electrochemical redox reactions, leading to improved charge storage capabilities.
- Metal ferrites provide additional redox-active sites, increasing the overall capacitance and energy density of the electrode.

i) Role of Reduced Graphene Oxide (rGO) in Electrode Performance

rGO has been extensively used in energy storage applications due to its exceptional electrical conductivity, large surface area, and lightweight nature. When combined with PPy and metal ferrites, rGO further enhances the electrode's performance.

i) Enhanced Electrical Conductivity

- ii) rGO acts as an efficient conductive network, facilitating rapid electron transport within the electrode material.
 - The high conductivity of rGO reduces charge transfer resistance, ensuring fast charge-discharge cycles in energy storage devices.

iii) Large Surface Area and Porous Structure

- The two-dimensional structure of rGO provides a high surface area, increasing the number of active sites for charge storage.
- The interconnected porous structure enhances electrolyte penetration, leading to better ion diffusion and charge retention.

iv) Structural Stability and Flexibility

- rGO improves the mechanical strength of the electrode, preventing material degradation and ensuring prolonged operational stability.
- The flexibility of rGO allows for the development of flexible and wearable energy storage devices.

ii) Metal Ferrite Doping for Enhanced Energy Storage

Metal ferrites such as nickel ferrite (NiFe_2O_4) and strontium ferrite (SrFe_2O_4) are known for their high electrochemical activity, stability, and redox capabilities. When incorporated with PPy and rGO, these ferrites further improve the electrode's performance.

i) Redox-Active Sites for Pseudocapacitive Behavior

- Metal ferrites undergo reversible redox reactions, contributing additional capacitance to the electrode.
- The presence of transition metal ions such as Ni^{2+} and Fe^{3+} enhances faradaic charge storage mechanisms.

ii) Improved Electrochemical Stability

- Ferrites provide structural integrity to the electrode, preventing degradation over long charge-discharge cycles.
- The incorporation of metal ferrites minimizes electrode swelling, ensuring

stable performance in aqueous and non-aqueous electrolytes.

iii) Synergistic Effect with PPy and rGO

- The combination of metal ferrites, PPy, and rGO results in a hybrid electrode material with enhanced energy density and power density.
- This synergistic effect allows for the development of high-performance supercapacitors and batteries with prolonged cycle life [62,63].

1.7 Metal doping and demonstrations

Adding heteroatoms to graphene networks is a powerful way to make ions move more easily between cathodes, anodes, and electrolytes. This change improves the capacitive performance by speeding up electron transfer reactions. This makes graphene-based materials better for storing energy. Adding heteroatoms changes the electronic structure of graphene, which makes it more conductive and improves how charges move through it. The improvements are especially helpful for making electrodes in supercapacitors and batteries work better. There are two main ways to explain how metal oxides act like capacitors: faradaic redox reactions and the electrochemical adsorption/desorption of ions at the terminal/electrolyte interface. When you compare metal oxides to regular carbon-based materials used in electric double-layer capacitors you can see that they have a much higher specific capacitance. This is because of the way they store charge. EDLCs only use electrostatic interactions to store charge, but pseudo-capacitive electrodes use reversible redox reactions to store energy, which increases capacitance. Both pseudocapacitive cathodes and battery-type electrodes rely on faradaic charge transfer reactions. Still, their electrochemical and energetic behaviors are very different from each other. Pseudocapacitive electrodes have fast redox kinetics, which makes charge-discharge cycles faster and increases power density. Battery-type electrodes, on the other hand, usually have slower reaction kinetics but can store more energy. This important difference makes pseudocapacitive materials perfect for uses that need quick energy release and long cycle life. Nickel and iron are great catalysts and are used a lot in technologies for storing and converting energy. Because of their amazing electrochemical activity and redox properties, they are great candidates for the development of high-performance electrode materials. Nanoparticles of binary iron-nickel oxides (NiFe_2O_4) show a lot of promise for use in supercapacitors. When these

materials are mixed with rGO the electrochemical performance gets better. This is because nickel, iron, and graphene work together in a way that makes them stronger. NiFe_2O_4 and rGO work together to improve charge transport and provide structural stability, both of which are important for making energy storage systems last a long time. NiFe_2O_4 is a transition metal oxide that acts like a pseudo-capacitive electrode, while graphene acts like a capacitive electrode. By combining these two materials, it is possible to create an electrode that has excellent electrochemical stability and a higher charge storage capacity. The pseudo-capacitive and capacitive elements work together to make the charge storage more efficient, the specific capacitance higher, and the cycling stability better. This combination is especially useful in hybrid supercapacitors, where high energy density and power output are needed. Transition metal ferrites have also become important electrode materials, along with rGO. This is because they have unique redox properties, are very stable electrochemically, and work well with other materials in composite structures. Nickel-strontium (Ni-Sr) ferrites are a type of spinel ferrite that have very good electrical and magnetic properties. These materials are known for their ability to allow fast charge transport, which makes them useful for electrochemical energy storage. Adding Ni-Sr ferrites to composite electrodes makes them more conductive, increases their capacitance, and improves their overall electrochemical performance. To sum up, combining transition metal ferrites like NiFe_2O_4 and Ni-Sr ferrites with rGO makes a very good electrode material for supercapacitors. These materials use both pseudocapacitive and capacitive mechanisms to make the most of their ability to store charge. Because rGO can do reversible redox reactions and has a larger surface area and higher conductivity, it is a better choice for advanced energy storage technologies[64,65].

1.8 Doping of Polymers

Even though binary hybrids have promising electrochemical properties, they still face a number of problems that make them less effective for storing energy. One big problem with pseudocapacitive materials is that they rely on diffusion-controlled redox reactions, which means that energy density and power density have to be balanced. As energy density goes up, the ability to provide high power output often goes down. This

limitation makes it very hard to create materials that can store a lot of energy and charge and discharge quickly at the same time. Another problem with binary hybrids is that they can build up pseudocapacitive particles, which could make the surface area smaller and make diffusion more difficult. It's very important to have a larger surface area for the best ion transport and charge storage, but having too many particles can make electrochemical performance worse. Also, for these materials to transport charge well, there needs to be strong and stable interactions at the interfaces between graphene and metal oxides. If these interfaces don't interact enough, it could lead to less efficient electron transfer and lower overall conductivity. To get around these problems, a conducting polymer layer is added to the graphene/oxide binary system. Adding conducting polymers makes a big difference in a number of electrochemical parameters, such as specific capacitance (Cs), Coulombic efficiency, and rate performance. Adding a conducting polymer layer to the composite improves charge transfer kinetics, electrical conductivity, and electrochemical stability. This change effectively solves the problem of balancing energy and power, letting the material keep both high energy density and power density. With these new developments, it's clear that ternary hybrids that combine graphene, metal oxides, and conducting polymers are a great choice for high-performance capacitive electrode materials. The materials work together to combine the advantages of graphene's large surface area and good conductivity, metal oxides' pseudocapacitive properties, and conducting polymers' flexibility and ability to store charge. So, more research is needed to fully understand their potential and improve their composition and processing methods for better performance. Conducting polymers are widely used in supercapacitors because they have high capacitance, good conductivity, and very low equivalent series resistance. The materials have a large surface area and can store redox energy, making them very good electrode materials for supercapacitors. Also, it is possible to add impurities to conducting polymers to make them conduct electricity like metals, which is a desirable property for anode materials in supercapacitors. Their adjustable electrical properties make it possible to store charge more effectively and cycle charge and discharge more quickly. Composites made from conducting polymers often have better electrochemical performance than regular activated carbon materials. They are great for storing energy because they have very high electrical conductivity and can do reversible redox

reactions. This makes them very appealing for next-generation supercapacitors[66]. Polypyrrole (PPy) is regarded as a superior option for hybrid electrode material composites, attributed to its distinctive blend of electrical, electrochemical, mechanical, and chemical characteristics. This is the reason it is distinctive:

i) Excellent Electrochemical Performance

- **High Capacitance:** PPy provides high specific capacitance ($\sim 400\text{--}600\text{ F/g}$) due to its redox activity, making it ideal for supercapacitors and batteries.
- **Fast Charge-Discharge:** Enables rapid ion diffusion and electron transport, improving electrochemical kinetics.
- **Reversible Redox Reactions:** Facilitate efficient energy storage and conversion.

ii) Strong Synergy with Other Materials

- **Carbon-Based Composites (Graphene, CNTs, Carbon Fibers):** PPy enhances conductivity and capacitance while providing structural flexibility.
- **Metal Oxides:** Improves charge storage capacity, stability, and catalytic properties.

iii) Mechanical Flexibility & Structural Stability

- **Flexible and Stretchable:** Unlike brittle inorganic materials, PPy can conform to various electrode architectures.
- **Prevents Electrode Cracking:** Acts as a binder to reinforce composite structures, minimizing mechanical degradation over cycling.
- **Good Adhesion:** Improves stability in hybrid electrodes, reducing material loss over repeated use.

iv) Chemical Stability & Compatibility

- **Stable in Various Electrolytes:** Works in both acidic and neutral environments without rapid degradation.

Doping Stability: Retains electrical properties over time, which is crucial for long-term applications.

- **Corrosion Resistance:** Helps protect metal-based components in the composite.

v) Easy Synthesis & Scalability

- **Simple Polymerization Methods:** Can be synthesized via chemical or electrochemical polymerization, enabling cost-effective large-scale production.

- **Versatile Morphologies:** Can be fabricated as thin films, nanostructures, coatings, or 3D networks for different applications.

vi) Applications of PPy-Based Hybrid Electrodes

- **Supercapacitors:** PPy-carbon composites enhance energy and power density.
- **Batteries (Li-ion, Na-ion, Zn-air):** Improves conductivity and charge storage.
- **Fuel Cells & Electrocatalysis:** Enhances oxygen reduction and hydrogen evolution reactions[67-69].

A three-component or ternary system has been proposed to enhance the performance of supercapacitors by integrating these three components. The combination of PPy, rGO, and Ni-Sr ferrites in a nanocomposite structure is anticipated to yield a high-performance electrode material characterized by enhanced electrochemical stability, charge storage capacity, and conductivity. This study aimed to explore the electrochemical performance of the ternary composite material, evaluate the contributions of each component and their synergistic effects, and demonstrate its potential application in the development of high-performing supercapacitors.

Nickel-strontium ferrites demonstrate remarkable magnetic and electrochemical properties, positioning them as promising options for improving charge storage capabilities. Integrating Ni-Sr ferrites with rGO and polypyrrole allows for the development of a multifunctional electrode material that harnesses the benefits of each component. This study examines the synthesis and characterization of polypyrrole-doped rGO/Ni-Sr ferrite nanocomposites, exploring their potential as electrode materials for supercapacitors. This investigation focuses on the structural, morphological, and electrochemical characteristics of the hybrid materials, offering valuable insights into their charge storage mechanisms and overall performance. The effective creation of these nanocomposites may play a significant role in enhancing high-performance supercapacitors for future energy storage solutions. Carbon nanotubes (CNTs), activated carbon, and graphene represent some of the carbon compounds that make up EDLCs. The rapid and reversible faradic processes occurring on the surface of the electrode material form the foundation for the pseudocapacitive mechanism. EDLC materials exhibit a low energy density, yet they demonstrate enhanced performance over time along with a higher power density. Conversely, despite possessing a higher energy density, pseudocapacitors exhibit a reduced power density due to their constrained electrical conductivity and

insufficient rate capabilities. Hybrid supercapacitors, integrating the optimal features of both categories, consist of materials utilized for both EDLC and pseudocapacitors. Recently, the utilization of carbon-based materials and polymer-nanofiller composites has proven effective in improving supercapacitor performance, leveraging significant synergistic effects. Devices utilizing supercapacitors can be constructed with 2D reduced graphene oxide-based electrode materials due to their extensive surface area, exceptional chemical durability, and electrical conductivity. The enhanced specific capacitance observed in the composite electrodes primarily results from the interconnected conductive network of the composite and the synergistic advantages of metal ferrite and graphene. Due to its remarkable electrical conductivity, extensive specific surface area ($\sim 2630 \text{ m}^2 \text{ g}^{-1}$ for single-sheet graphene, and flexibility stemming from its two-dimensional structure, graphene is considered one of the most promising materials for electric double-layer capacitors. Nonetheless, p-p stacking leads to the unavoidable reattachment of graphene sheets during electrochemical charge-discharge cycles, which diminishes its surface area. Consequently, it continues to be a challenge to ensure sufficient electrolyte diffusion across the entire surface area of graphene, especially at elevated current densities. One approach to minimizing graphene restacking involves organizing graphene layers into a well-defined, three-dimensional network. Additionally, addressing the limited diffusion of electrolyte ions during the deposition of pseudocapacitive compounds onto surface-functionalized graphene presents another strategy. The materials enhance energy density by facilitating multiple-fold capacitance via surface redox reactions, while also serving as a physical barrier to inhibit stacking. Therefore, it is essential to develop novel pseudocapacitive materials that are affordable, abundant, and exhibit high redox activity. In this sense, metal oxides have garnered significant interest from the academic community. The notable specific capacitance exhibited by ferrites and transition metal oxides (TMOs) has garnered interest in their potential application as electrode materials in supercapacitor devices. A variety of investigations have been carried out on metal ferrites exhibiting varying redox states as promising electrode materials for supercapacitor applications. Binary hybrids have been developed by combining graphene and spinel ferrites, resulting in improved electrochemical properties. Graphene oxide and metallic salts are

commonly employed as precursors for these hybrids. Graphene oxide is diminished either during or following the preparation process to yield reduced graphene oxide. Nonetheless, these binary hybrids continue to present several limitations. Initially, it is important to note that diffusion plays a critical role in the redox reactions of pseudocapacitive materials, often leading to an increase in energy density that is accompanied by a decrease in power density. Additionally, the accumulation of pseudocapacitive particles could lead to a reduction in surface area and an increase in diffusion resistance. Thirdly, effective charge transport necessitates close contact between graphene and oxide interfaces. To tackle these issues, a conducting polymer layer is applied to the graphene oxide, leading to significant enhancements in various electrochemical characteristics, including Cs, Coulombic efficiency, and rate performance. The study of conducting polymers in pseudocapacitors has garnered significant attention in recent years due to their impressive specific capacitance, attained through reversible redox reactions. Polypyrrole is a conducting polymer that exhibits remarkably high conductivity along with impressive mechanical and environmental durability. Therefore, it is clear that ternary hybrids utilizing graphene present promising possibilities for high-performance capacitive electrode materials, and further investigation is necessary to deepen our understanding of them. NiFe_2O_4 , a faradic type electrode material, is notably favored for its abundance in the earth's crust, low cost, and environmentally friendly properties. Nickel ferrite presents a compelling option owing to its favorable conductivity, non-toxic nature, abundance, and cost-effectiveness. The electrochemical properties of NiFe_2O_4 are determined by its structure and morphology, which can be readily modified through various synthesis factors. There is significant interest in strontium ferrite (SrFe_2O_4) due to its remarkable chemical stability, affordability, high saturation magnetization, and magneto-crystalline anisotropy. The material exhibits outstanding physical and chemical stability, along with a minimal coefficient of thermal expansion. The characteristics of this specific doped ferrite structure render it appropriate for energy storage applications. Strontium ferrite exhibits a high Curie temperature, remarkable magnetic properties, significant electrical resistance, and outstanding chemical stability. This project aims to develop an energy storage device that can efficiently store a substantial amount of electrical energy to address the growing demands for

energy storage in today's world. To develop electrodes with exceptionally high capacitance, we introduce a simple and scalable approach for producing binary composites as electrode materials. This approach integrates conductive polymer (polypyrrole), reduced graphene oxide, and metal ferrite (Ni-Sr Ferrite). Polymer-based composites have attracted considerable attention due to their ease of processing, flexibility, and adjustable properties. The distinctive blend of electrical conductivity, environmental stability, and flexibility positions polypyrrole as a highly promising material for a range of applications across both industrial and academic fields. The increasing focus on ferrites in recent decades can be attributed to their promising applications as electrode materials for energy storage devices, especially in supercapacitors. Their distinctive blend of electrical conductivity, electrochemical stability, and elevated specific capacitance positions them as highly promising options for advanced energy storage solutions. This study emphasizes the advancement of economical electrode materials that exhibit improved electrochemical performance. In pursuit of this goal, we developed an asymmetric supercapacitor electrode made from polypyrrole and nickel strontium ferrite (Ni-SrFe₂O₄), designated as PNS. The composite electrode was created through the sol-gel auto-combustion technique and then applied to the surface of nickel foam, which acts as a conductive substrate. The combination of PPy with pseudo-capacitive NiSrFe₂O₄ presents several benefits for enhancing charge storage capabilities. Polypyrrole, known for its conducting properties, offers significant electrical conductivity and numerous active sites for charge transfer. Meanwhile, Ni-SrFe₂O₄ enhances pseudocapacitive behavior, thereby improving the overall charge storage mechanism. The interaction between these materials promotes swift ion diffusion, resulting in quicker charge transfer and enhanced electrochemical reaction kinetics. The improved conductivity and charge transfer capability significantly contribute to enhancing the overall performance of the supercapacitor electrode [70-75]. This study aimed to analyze the electrochemical properties of the binary composite material, assess the individual contributions of PPy and Ni-SrFe₂O₄, and investigate the impact of their combination on supercapacitor performance. Electrochemical testing was conducted, utilizing techniques such as cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS), to evaluate essential performance metrics including

capacitance, charge retention, and cyclic stability. The results of this study indicate that the PNS composite electrode shows enhanced electrochemical performance when compared to its components, confirming its potential as a high-performance electrode material. The findings indicate that this composite holds promise for advancing next-generation asymmetric supercapacitors, providing a combination of high energy density, power capability, and long-term stability. This study enhances energy storage technologies by refining material synthesis and electrode fabrication techniques for ferrite-based electrode materials. Nickel (Ni) and strontium (Sr) were chosen as doping elements for iron oxide because of their remarkable redox properties and capacity to improve electrochemical performance. The cost-effectiveness, environmental friendliness, and outstanding electronic conductivity of these metals position them as prime candidates for enhancing the electrochemical properties of iron oxide-based materials. Their integration into the iron oxide matrix markedly enhances gravimetric capacitance, surpassing pure iron oxide regarding charge storage capacity and energy density. The electrodes made from rGO and Ni-Sr ferrite demonstrate remarkable electric double-layer capacitance characteristics, mainly due to the high surface area and exceptional electrical conductivity of rGO. The incorporation of rGO in the composite enhances charge transport efficiency and accelerates ion diffusion, rendering it exceptionally appropriate for energy storage applications. Furthermore, the addition of Ni-Sr ferrite significantly boosts the electrode's electrochemical performance by creating redox-active sites, which results in enhanced pseudocapacitive behavior. Conversely, electrodes made from PPy and Ni-Sr ferrite exhibit exceptional electrochemical stability along with increased specific capacitance. The combined influence of PPy's conjugated polymer structure, known for its remarkable electrical conductivity and flexibility, along with the redox-active sites of Ni-Sr ferrite, leads to improved charge storage capacity. This combination results in enhanced pseudocapacitive performance, improved cyclic stability, and extended operational life. The addition of Ni and Sr to ferrite-based composites significantly improves both EDLC and pseudocapacitive characteristics, positioning them as highly promising candidates for advanced energy storage solutions like supercapacitors.

Chapter 2

Review of Literature

2.1 Introduction

This study presents the synthesis and performance of binary and ternary composite electrodes for supercapacitor applications, motivated by previous investigations. The electrodes are specifically designed by combining conductive polymers, graphene, and mixed-doped metal (Nickel, Strontium) ferrite, highlighting their unique qualities and complementary effects. The advancement of sophisticated electrode materials is essential for improving the efficiency of energy storage systems. Among various materials, PPy, rGO and ferrites have attracted considerable interest owing to their distinctive characteristics. This work explores the synthesis and characterization of polypyrrole-doped rGO/Ni-Sr ferrites, along with their applications as electrodes in energy storage devices. The selected components for the proposed ternary system (PPy/rGO/MeFe₂O₄) include conductive polypyrrole (PPy) polymer, metal-doped iron oxide (MeFe₂O₄), and rGO to effectively demonstrate this concept. Two metals, Ni and Sr, were selected as model dopant elements for iron oxide because of their exceptional redox behavior. The metals in question are cost-effective, environmentally friendly, and exhibit excellent electronic conductivity and electrochemical performance, thereby enhancing gravimetric capacitance more efficiently than pure iron oxide. This study demonstrates the performance of the rGO-doped metal ferrite (nickel-strontium) composite as an active electrode upon the addition of polypyrrole. Graphene, a two-dimensional carbon material, exhibits exceptional electrical conductivity, mechanical strength, and a high specific surface area, rendering it highly suitable for energy storage applications. rGO obtained from graphene oxide (via reduction processes, maintains numerous beneficial properties of graphene while providing functional groups that enhance composite formation. The integration of rGO into electrode materials demonstrates enhancements in electrical conductivity and structural integrity. Spinel-type ferrites, such as nickel ferrite (NiFe₂O₄), exhibit notable magnetic properties and have been investigated for their potential in energy storage, attributed to their redox activity and stability. The process of doping ferrites with various metal ions,

including strontium (Sr), can alter their electrical and magnetic characteristics, which may improve their effectiveness in electrochemical applications. The incorporation of polypyrrole into the rGO/Ni-Sr ferrite composite can be achieved through either chemical oxidative polymerization or electrochemical polymerization methods. This process improves the electrical conductivity of the composite and introduces extra pseudocapacitive behavior, which is advantageous for energy storage applications. The integration of electric double-layer capacitance from rGO with pseudocapacitance from PPy and Ni-Sr ferrites leads to enhanced specific capacitance. The composites exhibit remarkable cycling stability, effectively tackling the prevalent challenge of swift capacitance decline in conducting polymers. The combination of Ni-based materials with graphene, carbon nanotubes, porous carbon, and activated carbon has notably propelled the development of supercapacitor technology. The development of energy storage devices with remarkable energy and power densities has been made possible through these innovative material combinations. The resulting supercapacitors exhibit an impressive energy density of up to 10 kW kg^{-1} , indicating their high efficiency for long-term energy storage. Their elevated energy capacity renders them particularly advantageous for use in renewable energy systems, electric vehicles, and portable electronic devices. Furthermore, these supercapacitors demonstrate a power density reaching 100 W h kg^{-1} , facilitating swift energy discharge to satisfy elevated power requirements. This feature proves to be especially advantageous in scenarios that demand rapid energy releases, including regenerative braking and emergency power backup systems. Moreover, the elevated specific capacitance of these supercapacitors guarantees effective energy storage and rapid charge-discharge cycles, improving their applicability in practical scenarios. The advancement of supercapacitors utilizing Ni materials alongside graphene, CNTs, porous carbon, and activated carbon has unveiled new opportunities for enhanced energy storage solutions. These supercapacitors, characterized by their remarkable properties present a promising and sustainable approach for addressing future energy storage requirements.

2.2 Literature Review:

Manju Kurian et al. indicated that ferrites can be generally divided into two main categories according to their magnetic properties: hard ferrites and soft ferrites. The classification is based on factors such as coercivity, remanence, and overall magnetic

behavior, which play a crucial role in their applications across different technological domains. Hard ferrites, including strontium ferrite and cobalt ferrite (CoFe_2O_4), exhibit high coercivity and notable remanence, allowing them to maintain their magnetization once the external magnetic field is withdrawn. The characteristics of these materials render them highly suitable for uses that demand permanent magnets, data storage solutions, and magnetic recording devices, where maintaining a stable and enduring magnetic state is crucial. Conversely, soft ferrites such as zinc ferrite (ZnFe_2O_4) and manganese ferrite (MnFe_2O_4) demonstrate low coercivity and low remanence, which allows them to be highly responsive to external magnetic fields, yet they are unable to maintain magnetization after the field is withdrawn. This feature renders them appropriate for applications in transformers, inductors, electromagnetic shielding, and high-frequency scenarios, where swift magnetization and demagnetization are essential. To further enhance the magnetic and electrical properties of ferrites, investigations have focused on the development of core-shell nanostructures, which integrate hard and soft ferrites into a single composite material. Integrating hard magnetic cores with soft magnetic shells allows these nanostructures to utilize the advantages of both ferrite types, leading to optimized magnetic behavior, enhanced electrical conductivity, and improved thermal stability. These hybrid materials exhibit considerable promise for sophisticated energy storage systems, spintronic devices, and multifunctional magnetic applications. This study highlights the significance of adjusting ferrite compositions to create high-performance materials with customized magnetic and electrochemical properties, broadening their applicability in diverse industrial and technological fields[76].

M. Fu et al. discovered that the sol-gel combustion method yields strontium-doped cobalt ferrite nanoparticles, with their electrochemical characteristics assessed through galvanostatic measurements, showcasing their potential to improve electrode performance in energy storage devices. The team utilized the sol-gel combustion method, which is a cost-effective, straightforward, and low-temperature synthesis technique, to create highly uniform and well-dispersed Sr-doped cobalt ferrite nanopowder. This technique is well-regarded for its capacity to produce high-purity materials with precise control over particle size and morphology, positioning it as an optimal strategy for the large-scale manufacturing of functional nanomaterials. The

addition of strontium (Sr) to the cobalt ferrite (CoFe_2O_4) framework is intended to enhance important electrochemical characteristics, including electrical conductivity, charge storage capacity, and structural stability. Through the modification of the ferrite composition via Sr doping, the aim was to optimize the electronic structure and enhance redox-active sites, ultimately improving the overall electrochemical performance of the material. The sol-gel combustion method employed in this study presents numerous benefits compared to conventional synthesis techniques. This approach allows for accurate stoichiometric control, consistent mixing of precursor materials, and the capability to synthesize nanomaterials at comparatively low temperatures. The formation of nanosized Sr-doped cobalt ferrite particles is influenced by these factors, leading to an increased surface area that is essential for effective charge transport and ion diffusion in energy storage applications. The results underscore the promise of Sr-doped cobalt ferrite as an effective electrode material for supercapacitors and various energy storage applications. This study highlights the significance of doped ferrite materials in the progression of next-generation energy storage devices, providing an effective and scalable pathway for the creation of high-capacitance, long-cycle-life electrode materials[77].

A.Moyse Owicz et al. present a polypyrrole/ Fe_2O_3 /reduced graphene oxide (PFG) ternary composite that was synthesized through a straightforward two-step procedure. The approach utilized hydrothermal synthesis to create the Fe_2O_3 /reduced graphene oxide (FG) composite, which was subsequently subjected to oxidative polymerization of pyrrole on its surface. The structural characterization revealed the presence of the α - Fe_2O_3 phase in both the binary and ternary composites, demonstrating successful material formation. Electrochemical investigations revealed that the binder-free PFG composite displays exceptional energy storage capabilities. In a 1 M Na_2SO_4 electrolyte, the PFG electrode exhibited a notable specific capacitance of 140 F/g at a current density of 1 A/g. Moreover, it exhibited an impressive capacitance retention of 93% following 5000 charge-discharge cycles, highlighting its durability over time. The enhanced performance results from the synergistic interaction between polypyrrole and the FG composite, leading to improved charge transport and electrochemical activity. The integration of polypyrrole, Fe_2O_3 , and reduced graphene oxide significantly contributes to the improvement of electrochemical performance. Polypyrrole establishes a conductive framework that enhances charge storage, whereas Fe_2O_3 plays a role in redox

processes. Reduced graphene oxide, recognized for its remarkable electrical conductivity and extensive surface area, significantly boosts the overall capacitance by facilitating ion diffusion and enhancing electron transport. The successful combination of these elements leads to a composite material characterized by elevated capacitance and stability, positioning it as a strong contender for supercapacitor applications. The impressive electrochemical stability of the PFG composite highlights its promising applications in energy storage systems. The sustained capacitance retention across numerous cycles suggests negligible structural degradation, rendering it appropriate for extended use. In contrast to traditional electrode materials, the PFG composite demonstrates enhanced charge-discharge efficiency, guaranteeing dependable performance in real-world applications. This study clearly illustrates that the straightforward two-step synthesis method successfully yields a high-performance electrode material characterized by outstanding electrochemical properties. The binder-free design streamlines the fabrication process, removing possible complications linked to polymeric binders. The PFG composite, with its promising performance, warrants further exploration for large-scale supercapacitor applications. Future endeavors could focus on refining synthesis parameters, investigating various electrolytes, and incorporating the composite into functional energy storage devices to improve its usability [78].

T.V.Thu et al. The integration of diverse materials serves as a potent method to improve properties for a range of applications. This study involves the chemical growth of a conductive polymer, PPy, on graphene-supported manganese ferrite microspheres (MG) to produce PPy/MG hybrids with different PPy contents (20, 33.3, and 42.9 wt%). The structural, morphological, and electrochemical characteristics of PPy, MG, and their hybrids were meticulously examined to gain insights into their performance enhancements. The electrochemical testing revealed that the PPy/MG hybrids demonstrated markedly superior capacitive properties in comparison to their separate components. The optimized hybrid reached a peak specific capacitance of 147.2 F/g at a scan rate of 10 mV/s and 66.1 F/g at a current density of 0.5 A/g. This improvement can be linked to the combined effects of PPy and MG, which lower diffusion resistance and enhance charge storage capabilities. The results underscore a

promising strategy for the advancement of high-performance materials intended for supercapacitor electrodes[79].

Kulandaivalu, S et al. synthesized samples of polypyrrole (PPy) effectively through the Chemical Oxidative Method, utilizing ferric chloride (FeCl_3) as the oxidant. The findings indicated that FeCl_3 had a considerable impact on the electrical and thermal characteristics of the synthesized PPy. The analysis of the effects of FeCl_3 and pyrrole monomer concentrations indicated that an increase in FeCl_3 concentration up to 2 M resulted in reduced resistivity, thereby enhancing conductivity. The investigation revealed that the morphological features of PPy significantly contribute to the improvement of conductivity. Structural and morphological analyses conducted through FTIR, XRD, and SEM validated the successful synthesis of the polypyrrole polymer. Furthermore, the most conductive PPy samples exhibited significant ammonia gas sensing abilities. A flexible and free-standing bilayer composite film was created by stacking a multiwalled carbon nanotube/reduced graphene oxide/nanocrystalline

cellulose (MWCNT/rGO/NCC) composite onto a polypyrrole/reduced graphene oxide (PPy/rGO) layer. The film was created through in-situ polymerization and vacuum filtration, subsequently undergoing chemical reduction with hydrazine vapor, and was evaluated as an electrode material for supercapacitors. The incorporation of nanocrystalline cellulose significantly reduced the aggregation of MWCNTs and graphene oxide, enhancing ion mobility within the composite. The resulting symmetrical supercapacitor combined both pseudocapacitive and electrical double-layer capacitor features, resulting in outstanding electrochemical performance. The device exhibited a specific capacitance of 882.2 F/g, maintained strong cycling stability of approximately 90% over 10,000 cycles, and achieved an energy density of 44.6 Wh/kg alongside a power density of 2889.9 W/kg. The findings suggest that the bilayer composite shows significant potential as a material for advanced energy storage applications, surpassing the performance of numerous previously documented polypyrrole-based supercapacitors[80].

Li, S., Zhang, L. et al. Synthesised three-dimensional TiO_2 @PPy/rGO nanocomposites were successfully achieved through a polymerization process. The process included the coating of TiO_2 nanoparticles with polypyrrole (PPy) to produce core-shell TiO_2 @PPy

nanospheres, which were subsequently integrated with graphene oxide (GO) via self-assembly to yield the final ternary nanocomposite. The robust interactions between $\text{TiO}_2@\text{PPy}$ and reduced graphene oxide (rGO) markedly improved electrochemical performance. The $\text{TiO}_2@\text{PPy}/\text{rGO}$ electrode demonstrated superior specific capacitance, reduced charge transfer resistance, and enhanced cycling stability when compared to $\text{TiO}_2@\text{PPy}$ nanospheres alone. The incorporation of rGO significantly improved the stability of PPy, leading to enhanced capacitive performance. The nanocomposite reached a peak specific capacitance of 462.1 F/g when tested at a current density of 0.5 A/g. This method offers a robust strategy for advancing the development of next-generation electrode materials intended for energy storage applications[81].

According to **Dhas, S. D.**, Nickel-based oxides are considered highly promising materials for pseudocapacitive electrodes, attributed to their cost-effectiveness, clear redox characteristics, and the potential for microstructure optimization via synthesis adjustments. Nonetheless, achieving a consistent morphology on conductive substrates like FTO, ITO, stainless steel, nickel foam, nickel mesh, and copper foam continues to pose a significant challenge. This study presents the synthesis of nickel oxide nanostructures (NiO-NSs) exhibiting high pseudocapacitive performance, achieved through the sol-gel technique for energy storage applications. The analysis through X-ray diffraction confirmed the monoclinic crystal structure of NiO-NSs, and X-ray photoelectron spectroscopy validated the oxidation states of nickel (+2) and oxygen (-2). Field-emission scanning electron microscopy displayed significant, irregular spherical clusters, while Brunauer-Emmett-Teller analysis suggested a mesoporous structure with a surface area of 31.4 m^2/g . The NiO-nickel foam (NF) electrode exhibited remarkable electrochemical characteristics, attaining a specific capacitance of 871 F/g at a scan rate of 5 mV/s in a 4 M KOH electrolyte. Furthermore, it demonstrated impressive cycling stability, maintaining 86.5% of its capacitance following 10,000 cycles. The mesoporous characteristics of NiO-NSs offered numerous active sites, promoting effective charge transport and improving electrochemical performance. A device featuring an asymmetric supercapacitor was constructed, utilizing NiO-NF for the anode and activated carbon nickel foam (AC-NF) for the cathode. This device achieved a specific energy of 24 Wh/kg with a power density of 2.9 kW/kg and maintained 89.7% of its capacitance after 5,000 cycles. The findings underscore the

promise of NiO-based electrodes in advancing high-performance energy storage solutions. In this study, hierarchical nickel sulfide (NiS) nanoparticles were effectively synthesized on nickel foam (NiS@Ni) utilizing a straightforward cathodic electrodeposition technique with an electrolyte made of nickel chloride (NiCl₂) and thiourea. The synthesized material underwent comprehensive analysis through a range of surface characterization techniques. The electrochemical performance of NiS@Ni as a positive electrode was assessed in an aqueous potassium hydroxide (KOH) electrolyte through CV and GCD methods. The CV and GCD curves demonstrated clear and distinct reversible redox peaks, validating its Faradaic battery-type behavior. The NiS@Ni electrode demonstrated remarkable specific capacities, achieving 1109 C/g (308.05 mAh/g) at a scan rate of 5 mV/s and 532 C/g (147.8 mAh/g) at a current density of 2 A/g. The findings suggest that hierarchical NiS@Ni shows significant potential as a battery-type positive electrode in hybrid capacitors[82].

Zha, D., Xiong, P., et al. shows hybrid nanostructures exhibiting robust electrochemical performance, characterized by high rate capability and extended cycling life, present economical alternatives for the energy storage devices of the future. This study presents the development of a ternary manganese ferrite/carbon black/polyaniline (MCBP) hybrid through a straightforward two-step synthesis, employing commercially available carbon black as an economical material. The interactions within this ternary nanostructure notably enhanced electrochemical properties. The hybrid exhibited an outstanding rate capability, achieving about 98% capacitance retention at a high current density of 40 A/g, and demonstrated remarkable cycling stability, retaining roughly 80% capacitance after 10,000 cycles at 5 A/g. Furthermore, a symmetric supercapacitor developed with the MCBP hybrid demonstrated exceptional performance, attaining more than 94% capacitance retention at 10 A/g and sustaining approximately 75% retention after 100,000 cycles at 5 A/g. The findings underscore the promise of this economical, high-efficiency hybrid material for use in commercial supercapacitor applications[83].

Sahoo, S., Zhang, S. et al. introduce an innovative porous ternary nanohybrid consisting of NiMn₂O₄, reduced graphene oxide, and polyaniline (GNMOP), designed as a high-performance electrode material for supercapacitors. The GNMOP hybrid was created through a hydrothermal-assisted thermal annealing method, followed by the in-

situ polymerization of polyaniline to improve conductivity. The electrochemical assessment revealed that GNMOP attained an impressive specific capacitance of 757 F/g at a current density of 1 A/g, markedly surpassing both the binary nanocomposite and conventional transition metal oxides. Furthermore, it demonstrated a peak energy density of 70 Wh/kg along with remarkable cycling stability, maintaining around 93% of its capacitance following 2,000 cycles. The improved performance can be linked to the efficient integration of its components and the conductive polyaniline wrapping, underscoring its promise as a sophisticated supercapacitor electrode material[84].

Iqbal, J., Ansari, et al present a ternary composite comprising carbon nanotubes, PPy, and hydrous MnO₂ synthesized through an in-situ chemical method and assessed for its electrochemical properties. The investigation further encompassed a comparative examination of two binary composites, CNT/hydrous MnO₂ and PPy/hydrous MnO₂, evaluating their structural and electrochemical properties. The electrochemical testing conducted in a 1.0 M Na₂SO₄ electrolyte through CV demonstrated that the ternary composite showed a markedly higher specific capacitance than the binary composites. At a scan rate of 20 mV/s, the specific capacitance values for the ternary CNT/PPy/MnO₂, CNT/MnO₂, and PPy/MnO₂ composites were 281, 150, and 35 F/g, respectively. At a higher scan rate of 200 mV/s, the values decreased to 209, 75, and 7 F/g. The cycling stability of the ternary composite electrode was investigated over 10,000 charge-discharge cycles within a voltage range of 0.1 to 0.9 V (vs. Ag/AgCl) at a rate of 100 mV/s, resulting in the electrode maintaining 88% of its initial capacitance. A complete cell constructed with the ternary composite electrodes demonstrated an initial specific capacitance of 149 F/g at a current density of 1.0 mA/cm². Nonetheless, following 2,000 cycles, this value decreased markedly to 35 F/g. The findings underscore the enhanced electrochemical performance of the ternary composite in comparison to its binary counterparts, positioning it as a promising candidate for energy storage applications[85].

Wang, C., Yang, Y., et al., comprising conducting polymer-coated graphene oxide and carbon nanotubes, composites were effectively produced through a one-step electrochemical co-deposition technique. The composites incorporated conducting polymers such as polypyrrole (PPy) and poly(3,4-ethylenedioxythiophene) (PEDOT). Structural analysis through SEM and transmission electron microscopy (TEM)

validated the development of a ternary hybrid microstructure, in which GO served as a substrate for CNTs enveloped in conducting polymers. The electrochemical evaluations, which included cyclic voltammetry, galvanostatic charge-discharge, and electrochemical impedance spectroscopy, revealed that the addition of CNTs markedly improved the capacitive performance of CPs-GO electrodes. Among the composites, PEDOT-GO/CNTs demonstrated the most significant electrochemical enhancement as the CNT content increased. The ternary PPy-GO/CNTs and PEDOT-GO/CNTs composites demonstrated impressive areal specific capacitances of 142.2 mF/cm² and 99.0 mF/cm² at a current density of 1.0 mA/cm², respectively. Furthermore, both composites exhibited remarkable rate capability and exceptional cycling stability, maintaining 97.3% and 99.2% of their initial capacitance after 5,000 cycles. The results underscore their promise as exceptional electrode materials for supercapacitor applications. PPy stands out as a highly investigated conducting polymer for application as a pseudocapacitive material, attributed to its various benefits such as affordability, flexibility, excellent electrical conductivity, environmental friendliness, and impressive stability in redox reactions. This set of characteristics positions it as a compelling option for energy storage applications, especially in the realm of supercapacitors. Nonetheless, in spite of these advantages, pure polypyrrole presents specific limitations that impede its sustained performance over time. A significant limitation is its comparatively low tensile strength, rendering it vulnerable to mechanical degradation after numerous charge-discharge cycles. Furthermore, throughout the charging and discharging phases, ions are in a constant state of insertion and extraction within the polymer framework. The continuous movement of ions induces structural alterations, resulting in volumetric expansion and contraction, which ultimately leads to mechanical stress and material fatigue. Over time, these effects lead to inadequate cycling stability, restricting the practical use of pure polypyrrole in advanced energy storage systems[86].

Abdillah, O. B., et al. worked to enhance the physical properties and electrochemical cycling stability of PPy. Various studies have incorporated carbon-based nanomaterials such as carbon nanotubes and graphene. The materials provide outstanding mechanical strength, electrical conductivity, and structural stability, addressing the inherent limitations of pure polypyrrole, including its low tensile strength and inadequate long-term cycling performance. Through the formation of composites with CNTs or graphene, PPy exhibits enhanced durability, superior charge transport properties, and

improved ion diffusion pathways, thereby increasing its suitability for energy storage applications. Alongside carbon-based materials, transition metal oxides and specific ferrites have garnered considerable interest as promising electrode materials for supercapacitors. In recent decades, these materials have been the subject of extensive investigation owing to their high specific capacitance, which is a result of their capacity for rapid and reversible redox reactions. Transition metal oxides, including manganese oxide, cobalt oxide, and nickel oxide, present a significant quantity of active sites for charge storage. In contrast, ferrites exhibit distinctive electrochemical characteristics that enhance energy storage capabilities. The integration of polypyrrole with these materials has demonstrated encouraging outcomes in improving the overall electrochemical efficiency and long-term stability of supercapacitor electrodes[87].

Thu, T. study outlines the chemical synthesis of polypyrrole (PPy) on manganese ferrite microspheres (MG) that are supported by graphene, resulting in the formation of PPy/MG hybrids with varying PPy concentrations. Characterization revealed enhanced morphological and structural characteristics. Electrochemical studies revealed that the PPy/MG hybrids exhibited significantly superior performance in capacitance compared to individual components, achieving a maximum specific capacitance of 147.2 F/g at 10 mV/s and 0.1 F/g at 0.5 A/g [88].

Sivakkumar, S. R. et al. present a chemical method conducted in its original place is utilized to create a ternary composite made up of CNTs, PPy and hydrous manganese dioxide (MnO_2). To deepen the understanding of the contributions from individual components, two binary composites/hydrous MnO_2 and polypyrrole/hydrous MnO_2 , are synthesized and tested. This allows for a comparison of their physical and electrochemical properties with those of the ternary composite. Conducting polymers (CPs) have attracted considerable interest in scholarly studies and commercial uses because of their distinctive capacity to merge the electrical properties of semiconductors and metals with the advantages of traditional polymers. The characteristics of these materials include straightforward synthesis, cost-effective processing, and mechanical flexibility, rendering them particularly appropriate for energy storage applications. This work offers an in-depth analysis of the role of conducting polymer-based composites in the development of supercapacitors and batteries. This study investigates various composite structures, such as binary, ternary, and quaternary composites, emphasizing their influence on electrochemical performance. The conversation explores how

conducting polymers contribute to the enhancement of charge storage mechanisms, the improvement of conductivity, and the increase in structural stability across different energy storage devices. This r provides a critical analysis of the advancements in the integration of these technologies into supercapacitors, lithium-ion batteries, and other ion-based batteries for their applications in energy storage. The essential design principles for enhancing energy storage performance, such as material selection, structural engineering, and electrolyte optimization, are also examined. Furthermore, the existing challenges associated with polymer-based composites, including stability concerns, capacity decline, and mechanical deterioration over extended usage, are examined. The review delves into prospective avenues for investigation that may improve their efficiency and expand their use in next-generation energy storage technologies. The evaluation of the electrochemical performance of these materials involves measuring their specific capacitance (SC) values in a 1.0 M Na₂SO₄ electrolyte solution. The analysis of the CV indicates that the ternary composite (CNT/Ppy/hydrous MnO₂) shows a markedly higher specific capacitance in comparison to the binary composites. At a scan rate of 20 mV/s, the specific capacitance values for the ternary composite, CNT/hydrous MnO₂ binary composite, and polypyrrole/hydrous MnO₂ binary composite are 281, 150, and 35 F g⁻¹, respectively. With an increase in the scan rate to 200 mV/s, the capacitance values are observed to decrease to 209, 75, and 7 F g⁻¹, respectively. The findings underscore the exceptional charge storage capacity of the ternary composite, showcasing improved electrochemical performance attributed to the synergistic interaction of CNTs, polypyrrole, and hydrous MnO₂, which together enhance conductivity, structural stability, and redox activity[89].

Nabeel et al. present a clear and scalable approach for developing binary and ternary composites tailored for electrode materials, specifically aimed at supercapacitor applications. The composites were synthesized through the integration of reduced graphene oxide (rGO) with NiCoFe₂O₄ metal oxides and the conductive polymer polypyrrole (PPy). This work is significant due to the advancement of supercapacitors, known for their impressive energy density, rapid charge and discharge capabilities, extended lifespan, and affordability. The binary compound, rGO/NiCoFe₂O₄, was synthesized through sol-gel auto-combustion, utilizing carbon cloth as the electrode substrate for electrochemical evaluation. The electrochemical investigation

demonstrated a specific capacitance of 154 F/g for the rGO/NiCoFe₂O₄ binary composite at a scan rate of 10 mV/s. The incorporation of PPy led to the formation of the ternary composite, PPy/rGO/NiCoFe₂O₄, which exhibited an improved C_{sp} of 210 F/g under identical conditions, highlighting the synergistic influence of PPy. The ternary composite exhibited C_{sp} values of 222.5 F/g at 1 A/g and 145 F/g at 2 A/g, whereas the binary composite demonstrated C_{sp} values of 157.1 F/g and 110 F/g, respectively, as per GCD analysis. This study's findings underscore the promising capabilities of the PPy/rGO/NiCoFe₂O₄ composite in the realm of high-performance supercapacitors, leveraging the synergistic advantages of rGO, NiCoFe₂O₄, and PPy to improve energy storage efficiency [90].

B. Jeewanantam et al. reported a sample of Co_{0.8}Sr_{0.2}Fe₂O₄, synthesized through the sol-gel auto-combustion method and exposed to a temperature of 300°C, that demonstrates remarkable electrochemical performance. At a current density of 0.5 A/g, this material exhibits a specific capacitance of 637 F/g. Additionally, the cycling stability is impressive, with the material maintaining 85.5% of its initial capacitance after 1000 charge-discharge cycles at a current density of 5 A/g. Furthermore, evaluations of long-term durability indicate that following 5000 cycles at 15 A/g, the material attains an impressive coulombic efficiency of 98.79%, validating its remarkable charge retention and reversibility. The results indicate that doped nano-ferrite materials, like Co_{0.8}Sr_{0.2} Fe₂O₄, demonstrate noteworthy electrochemical properties, positioning them as viable options for electrode materials in supercapacitor applications[91].

Feng et al. introduced a novel composite material for supercapacitors, featuring a nitrogen-doped porous carbon matrix integrated with polypyrrole (PPy). This composite design seeks to improve electrical conductivity and electrochemical stability, all while preserving a high specific capacitance. The incorporation of nitrogen doping into the porous carbon structure aims to enhance active sites for charge storage, boost wettability, and promote ion transport, ultimately optimizing the performance of supercapacitors. Following 1000 cycles, the PPy nanospheres that were consistently developed on the surface of the porous carbon matrix exhibited an impressive specific capacitance of 237.5 F g⁻¹, along with a discharge rate of 88.53%. By leveraging the

unique properties of PPy, characterized by its high capacitance and exceptional mechanical flexibility, wearable supercapacitors were developed through the growth of carbon nano-onion nanotubular arrays on fabric. The resulting hybrid nanostructures, derived from PPy and integrated with fabric materials, exhibited enhanced energy storage capabilities, achieving a specific capacitance of 64.0 F g^{-1} . The nanostructures exhibited notable elasticity. Moreover, following 500 stretching cycles, a capacitance retention of 99.0% was observed at a strain of 50.0% [92].

Ma, C et al. introduce a two-step production method that incorporates air-laid paper, reduced graphene oxide, and polypyrrole to create free-standing paper-based electrodes. The hybrid paper electrodes exhibit a high specific capacitance of 1685 mF cm^{-2} at 2 mA cm^{-2} , along with outstanding cycling stability, maintaining 92.8% of their capacitance after 5000 cycles, showcasing impressive electrochemical performance. This indicates that the electrodes are capable of maintaining functionality even after prolonged use, a crucial factor for practical applications[93].

Kumar, S et al. developed a CFO-PPy-NT composite that demonstrates potential for next-generation energy storage systems, especially in scenarios demanding high energy and power densities. The synthesis of CFO-PPy-NTs is achieved through a simple hydrothermal process. The CFO-PPy-NT electrode demonstrates a discharge capacity of 400 mAh g^{-1} , maintaining a stable Coulombic efficiency of 98% after 200 cycles at a current density of 100 mA g^{-1} . When subjected to a higher current density of 1000 mA g^{-1} , the electrode retains a discharge capacity of 220 mA h g^{-1} after 2000 cycles. Polypyrrole is extensively examined as a pseudocapacitive conducting polymer, attributed to its cost-effectiveness, flexibility, high conductivity, environmental compatibility, and stable redox properties. The study conducted by Biswas et al. examined the supercapacitor performance of a graphene/PPy nanocomposite, demonstrating a specific capacitance of 165 F g^{-1} at 1 A g^{-1} in a 1M NaCl aqueous electrolyte[94].

Tamilselvi, R. Novel nickel-based reduced graphene oxide (rGO) nanocomposites have been successfully synthesized, aimed at improving energy storage capabilities and photocatalytic performance. The synthesis process utilized an eco-friendly

hydrothermal method, incorporating rGO nanoflakes obtained from coconut coir biowaste as a sustainable precursor material. The nanoflakes were subsequently adorned with nickel oxide (NiO) and nickel ferrite (NiFe₂O₄) nanoparticles, resulting in hierarchical nanocomposites that exhibit enhanced structural and electrochemical properties. The electrochemical assessment of these nanocomposites demonstrated exceptional performance. The material exhibited an impressive specific capacitance of 599.9 F g⁻¹ at a current density of 1 A g⁻¹, highlighting its efficiency in charge storage and delivery. Furthermore, the composite demonstrated impressive long-term cycling stability, maintaining 86.5% of its initial capacitance after 2000 charge-discharge cycles, which highlights its exceptional durability and potential for real-world supercapacitor applications. The enhanced electrochemical performance of these nanocomposites results from the synergistic interactions between NiFe₂O₄ nanoparticles and rGO nanoflakes. The incorporation of NiFe₂O₄ boosts redox activity, leading to an increased charge storage capacity, whereas rGO offers superior electrical conductivity and structural stability, promoting effective electron and ion transport. The integration of these properties renders the synthesized material exceptionally promising for applications in renewable energy storage technologies and environmental remediation, such as photocatalysis for pollutant degradation and sustainable energy harvesting [95].

Sankar, K. V. et al. describe the synthesis of cobalt ferrite (CoFe₂O₄) nanoparticles through a polyethylene glycol-assisted solution combustion method, resulting in the creation of ultrafine particles with dimensions under 10 nm. The structural and phase purity of the synthesized nanoparticles was confirmed through XRD, FTIR, and Raman spectral analysis, which collectively validated the successful formation of a single-phase CoFe₂O₄ structure. The electrochemical analysis of the CoFe₂O₄ electrode demonstrated a specific capacitance of 195 F g⁻¹ at a scan rate of 1 mV s⁻¹, indicating that charge storage is primarily influenced by capacitive mechanisms. The results underscore the promise of CoFe₂O₄ as a highly effective material for use in supercapacitor applications[96].

Thu, T. investigates a novel method for improving energy storage capabilities through the chemical growth of polypyrrole (PPy) on graphene-supported manganese ferrite

microspheres (MG), leading to the creation of PPy/MG hybrid composites with different levels of polypyrrole content. A thorough analysis of these hybrids revealed notable enhancements in structural integrity and morphological characteristics, validating the effective incorporation of polypyrrole with the graphene-supported manganese ferrite microspheres. Electrochemical evaluations demonstrated the enhanced capacitive performance of the PPy/MG hybrids when compared to their components. The PPy/MG hybrid demonstrated a peak specific capacitance of 147.2 F g^{-1} at a scan rate of 10 mV s^{-1} , and at a current density of 0.5 A g^{-1} , the capacitance measured 66.1 F g^{-1} . The improved performance can be mainly linked to the collaborative interactions between polypyrrole and the manganese ferrite microspheres, resulting in decreased diffusion resistance and enhanced charge transfer efficiency. This study highlights the effectiveness of material hybridization in the development of high-performance supercapacitor electrodes, presenting a promising approach for the advancement of next-generation energy storage materials[97].

Vignesh, V. effectively synthesized manganese ferrite (MnFe_2O_4) nanoparticles through a chemical co-precipitation method, utilizing sodium hydroxide (NaOH) as the precipitating agent. The analyses validated the crystalline structure of MnFe_2O_4 , and the SEM images demonstrated that the nanoparticles displayed a spherical morphology with diameters varying from 20 to 50 nm. The electrochemical performance of the MnFe_2O_4 nanoparticles was evaluated using (CV) and (GCD) techniques across various electrolyte solutions. The findings revealed a significant difference in specific capacitance based on the type of electrolyte employed. The MnFe_2O_4 nanoparticles demonstrated a peak specific capacitance of 173 F g^{-1} in 3.5 M KOH , 31 F g^{-1} in 1 M LiNO_3 , and 430 F g^{-1} in $1 \text{ M Li}_3\text{PO}_4$, underscoring the effect of electrolyte composition on charge storage capabilities. Additional analysis of cycling stability and rate capability demonstrated that the MnFe_2O_4 nanoparticles exhibited remarkable long-term performance in 3.5 M KOH , maintaining 105% of their initial capacitance after 10,000 cycles at 1.5 A g^{-1} . This notable stability demonstrates the material's self-activation characteristics and its capacity to preserve structural integrity throughout prolonged charge-discharge cycles. This study highlights the efficacy of the chemical co-precipitation method as a cost-effective and scalable technique for the synthesis of MnFe_2O_4 nanoparticles exhibiting superior electrochemical performance. The findings illustrate their capability as reliable and efficient electrode materials for advanced

energy storage solutions, especially in supercapacitor uses[98].

Deshmukh, V. et al. performed an in-depth study on the electrochemical characteristics of cobalt (Co)-doped manganese ferrite (MnFe_2O_4) nanomaterials to improve their applicability in supercapacitor technologies. The investigation examined different concentrations of Co doping (2 wt%, 4 wt%, and 8 wt%) to identify the ideal composition for enhanced electrochemical performance. The 2wt% Co doped MnFe_2O_4 nanomaterial demonstrated the most favorable outcomes among the tested samples, reaching a peak specific capacitance of 551.39 F g^{-1} at a current density of 1 mA cm^{-2} . The notable enhancement in capacitance indicates that Co doping plays a crucial role in boosting the supercapacitive properties of MnFe_2O_4 . This improvement is likely attributed to factors such as increased electrical conductivity, better ion diffusion pathways, and heightened redox activity within the electrode material. The results of this study suggest that Co-doped MnFe_2O_4 composites exhibit significant promise as effective electrode materials for energy storage applications. The exceptional charge storage capacity, along with improved electrochemical stability, makes these materials highly promising for future supercapacitor applications. This study highlights the effectiveness of transition metal doping in enhancing the electrochemical properties of metal ferrites, setting the stage for their future application in advanced energy storage technologies [99].

Shih, K. Y., & Tseng, H. Y. (2025). shows the combination of MnFe_2O_4 nanorods with rGO successfully addresses the self-agglomeration challenge of rGO, leading to a well-dispersed structure and enhanced interfacial interactions. This distinctive configuration greatly improved charge transfer characteristics, leading to enhanced electrochemical performance. Electrochemical evaluations demonstrated that the $\text{MnFe}_2\text{O}_4/\text{rGO}$ composite achieved a remarkable specific capacity of 195 F g^{-1} at a current density of 1 A g^{-1} , considerably surpassing the performance of individual MnFe_2O_4 (77 F g^{-1}) and rGO (67 F g^{-1}). The composite electrode exhibited remarkable cycling stability, maintaining 75.22% of its initial capacitance following 4000 charge- discharge cycles at 2 A g^{-1} . Additionally, the asymmetric supercapacitor (ASC) device that includes the $\text{MnFe}_2\text{O}_4/\text{rGO}$ nanocomposite achieved an energy density of 16 W h kg^{-1} at a power density of 1280 W kg^{-1} . The ASC device exhibited 73.78% of its capacitance retention

after undergoing 5000 charge-discharge cycles, underscoring its impressive long-term stability. These findings highlight the benefits of integrating MnFe_2O_4 with rGO for energy storage applications. The improved electrochemical characteristics and longevity of $\text{MnFe}_2\text{O}_4/\text{rGO}$ nanocomposites position them as a strong contender for advanced supercapacitor technologies[100].

Wei, H. et al. explore the creation of polypyrrole (PPy)/cobalt oxide (Co_3O_4)/carbon paper (CP) ternary composites as innovative electrode materials for supercapacitor applications. The synthesis process entails the electropolymerization of pyrrole monomers onto flower-like Co_3O_4 (f- Co_3O_4) nanoparticles, which are directly deposited onto a carbon paper (CP) substrate. This fabrication technique guarantees robust interfacial adhesion among the components, resulting in a cohesive composite with improved electrochemical characteristics. The findings indicate that the PPy/f- Co_3O_4 /CP composite demonstrates superior performance compared to the other materials evaluated, attaining a specific capacitance of 398.4 F g^{-1} . In contrast, the f- Co_3O_4 /CP and ball-like Co_3O_4 /CP composites demonstrate significantly lower capacitance values of 40.9 F g^{-1} and 22.0 F g^{-1} , respectively. The significant increase in capacitance can be mainly ascribed to the pseudocapacitive characteristics of polypyrrole, along with the decreased charge transfer resistance due to the improved material structure. Furthermore, the PPy/f- Co_2O_4 /CP composite exhibits remarkable cycling stability, maintaining a substantial fraction of its initial capacitance after 1000 charge-discharge cycles, which underscores its durability and appropriateness for extended energy storage applications. The effective integration of polypyrrole's excellent conductivity, Co_3O_4 's notable electrochemical activity, and the strong structural support provided by carbon paper results in the enhanced performance of the ternary composite. This study emphasizes the capabilities of PPy/f- Co_3O_4 /CP as an advanced electrode material, presenting a promising strategy for improving the efficiency and lifespan of supercapacitors in future energy storage applications [101].

Tang, D. explores the synergistic combination of advanced electrochemical charge storage and spontaneous magnetization in cobalt ferrite (CoFe_2O_4 , CFO) and conducting polypyrrole (PPy) to develop high-performance electrode materials for pseudocapacitor applications. This investigation examines how the combination of PPy and CFO improves the electrochemical characteristics of the material, especially within

a Na_2SO_4 electrolyte, where the natural pseudocapacitive behavior of CFO is notably enhanced. Through the formation of CFO/PPy composites, materials with enhanced specific capacitance, reduced charge transfer resistance, and improved electrochemical stability are achieved. Electrochemical evaluations indicate that the CFO/PPy composites exceed the performance of their components, especially at elevated charging and discharging rates, highlighting their promise for high-power energy storage applications. The incorporation of PPy significantly reduces charge transfer resistance, enhancing ion diffusion and utilizing the pseudocapacitive characteristics of CFO. The combination of these two materials results in enhanced charge storage efficiency and improved electrochemical performance, rendering the composite more appropriate for applications that demand quick energy delivery. Nonetheless, the findings indicate that a rise in PPy content results in a reduction of relaxation frequency and capacitance retention, suggesting that achieving an optimal balance between CFO and PPy is essential for maximizing performance. Despite these variations, the CFO/PPy composites demonstrate significant potential for high-power pseudocapacitor applications, primarily owing to the magneto-hydrodynamic effect of CFO particles, which is essential in improving charge storage and transport properties. This study presents a novel method for advancing next-generation energy storage devices, showcasing the benefits of material hybridization in enhancing pseudocapacitor performance[102].

Hussein, O. presents the fabrication and electrochemical evaluation of polypyrrole nanofibers (PPy-NFs) and $\text{Co}_{0.2}\text{Zn}_{0.6}\text{Mn}_{0.2}\text{Fe}_2\text{O}_4$ ferrite nanoparticles, synthesized through chemical oxidative polymerization and the co-precipitation method, respectively. The structural and morphological characterizations of these materials were conducted utilizing field emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD). The FESEM images provide evidence that the PPy nanofibers are adorned with ferrite nanoparticles, resulting in a cohesive composite structure. Additionally, the XRD analysis substantiates the successful development of crystalline phases in both materials. Evaluations of electrochemical performance reveal notable charge storage capacities for each of the materials. PPy-NFs demonstrate a specific capacitance of 305 F g^{-1} , while the ferrite nanoparticles reach a capacitance of 230.01 F g^{-1} . The addition of ferrite nanoparticles to the PPy-NF matrix leads to improved

electrochemical activity, mainly resulting from the synergistic interaction between the conducting polymer and ferrite nanostructures. This interaction promotes more efficient charge transfer kinetics, boosts ion diffusion, and enhances redox performance. The results indicate that this synthesis method offers a highly efficient strategy for enhancing pseudocapacitive materials, rendering these composites appropriate for cutting-edge energy storage applications. The investigation highlights the promise of PPy-NF and ferrite nanoparticle-based hybrid materials in advancing next-generation supercapacitors, showcasing improved electrochemical properties and consistent redox behavior [103].

S. R. Sivakumar et al. created a ternary composite made up of carbon nanotubes (CNT), (PPy, and manganese dioxide (MnO_2), and performed an extensive evaluation of its electrochemical performance through (CV), GCD and (EIS). The aim was to evaluate the combined effects of these materials on enhancing charge storage capabilities, stability, and conductivity for possible supercapacitor applications. The ternary composite (CNT/PPy/ MnO_2) showed remarkable electrochemical performance when compared to its binary counterparts, highlighting enhanced specific capacitance and better cycling stability. The composite demonstrated a specific capacitance of 281 F g^{-1} at a scan rate of 20 mV s^{-1} , significantly surpassing the performance of the binary composites. Furthermore, the material demonstrated outstanding long-term cycling stability, maintaining 88% of its initial capacitance after 10,000 charge-discharge cycles, which reflects its strong structural integrity and electrochemical durability. This study underscores the potential of CNT/PPy/ MnO_2 composites as effective materials for high-performance supercapacitors, while also stressing the necessity for additional material optimization to reduce long-term degradation and improve overall cycling stability in practical energy storage systems[104].

Ansari Nowman et al. concentrated on creating binary and ternary composites designed for high-performance supercapacitor electrodes, highlighting energy density, swift charge/discharge abilities, and extended durability. The synthesis of these composites was achieved through a sol-gel method integrated with polymers, resulting in a material that exhibits a well-defined structure and improved electrochemical characteristics. The electrochemical evaluations demonstrated that the ternary

composite (PPy/rGO/NiCoFe₂O₄) exhibited a notable enhancement in specific capacitance compared to its binary counterpart (rGO/NiCoFe₂O₄). The ternary composite demonstrated a capacitance of 210 F g⁻¹ at a scan rate of 10 mV s⁻¹, while the binary composite showed a reduced capacitance of 154 F g⁻¹ under identical conditions. The significant enhancement in the performance of the ternary composite can be ascribed to the synergistic interaction among PPy, rGO and NiCoFe₂O₄, which together improve charge storage capacity, electrical conductivity, and ion diffusion. The findings indicate that incorporating PPy significantly enhances the overall electrochemical performance, facilitating improved charge transport and offering more active sites for energy storage. This improvement showcases how material hybridization can optimize supercapacitor electrodes, leading to enhanced efficiency in energy storage applications. Moreover, these results highlight the scalability and cost-effectiveness of the developed composites, positioning them as promising options for large-scale energy storage systems. The encouraging findings indicate that PPy/rGO/NiCoFe₂O₄ composites could play a crucial role in advancing supercapacitor technologies, providing an optimal combination of high energy density, rapid charge-discharge rates, and longevity for real-world energy storage solutions [105].

M. B. Akshari et al. achieved the successful synthesis of nickel ferrite (NiFe₂O₄) nanoparticles along with their hybrid composite with reduced graphene oxide (NiFe₂O₄/rGO) to investigate their potential as high-performance electrode materials for energy storage applications. The synthesis focused on improving the electrochemical properties of nickel ferrite through its integration with rGO, known for its excellent electrical conductivity, structural stability, and enhanced charge transfer kinetics. A thorough material characterization was performed utilizing XRD, and SEM. The analyses validated the successful creation of crystalline NiFe₂O₄ nanoparticles, their effective incorporation with rGO, and the existence of a highly porous structure that promotes efficient ion diffusion and charge storage. The electrochemical evaluations, comprising CV, EIS and GCD tests, highlighted the exceptional charge storage capabilities of the NiFe₂O₄/rGO hybrid composite. The material demonstrated a specific capacitance of 584.63 F g⁻¹, showcasing its effective capability to store and deliver charge. Furthermore, the long-term stability testing demonstrated impressive capacitance retention of 91% following 2000 charge-discharge cycles, underscoring its

robustness and appropriateness for real-world energy storage applications. The notable enhancement in electrochemical performance relative to pure NiFe_2O_4 can be largely ascribed to the synergistic interaction between nickel ferrite and rGO, with rGO boosting electrical conductivity and NiFe_2O_4 playing a role in redox-active charge storage. The findings highlight the promise of $\text{NiFe}_2\text{O}_4/\text{rGO}$ composites as effective electrode materials for supercapacitors, showcasing a blend of high capacitance, outstanding cycling stability, and efficient charge transport-crucial elements for the advancement of energy storage technologies[106].

Singh, M. presents the synthesis and detailed examination of Spinel $\text{FeMn}_x\text{Co}_{2-x}\text{O}_4$ ($x = 0, 0.1, 0.2, 0.4$) nanofibers, produced through the electrospinning method, to investigate their structural, magnetic, electrical, and electrochemical characteristics. The objective of this study is to examine the effects of Mn doping on the characteristics of FeCo_2O_4 nanofibers, with a specific focus on magnetoelectric coupling and their potential use in supercapacitor applications. The structural analysis confirmed the successful formation of spinel $\text{FeMn}_x\text{Co}_{2-x}\text{O}_4$, exhibiting a well-defined morphology and a uniform distribution of Mn, Fe, and Co throughout the nanofibers. Magnetic measurements demonstrated that the Mn-doped FeCo_2O_4 nanofibers displays ferromagnetic characteristics, with the peak magnetization value of 32 emu g^{-1} recorded for the sample with $x = 0.4$, suggesting improved magnetic interactions resulting from Mn substitution. In the course of the electrical transport analysis, it was observed that the $x = 0.2$ composition displayed the highest electrical conductivity, indicating an optimal balance between charge carrier mobility and structural stability. Furthermore, the introduction of an external magnetic field had a substantial impact on charge transport, leading to a twofold increase in conductivity for the $x = 0.4$ composition, which illustrates a robust magneto-electronic coupling within the system. The electrochemical investigations into the supercapacitive performance of the nanofibers demonstrated a notable enhancement in energy storage capabilities when subjected to a magnetic field, highlighting the multifunctional characteristics of Mn-doped FeCo_2O_4 . The findings demonstrate that the incorporation of Mn improves charge storage characteristics, positioning these nanofibers as strong contenders for applications in magnetoelectric and energy storage technologies. This investigation emphasizes the promise of Mn-doped FeCo_2O_4 nanofibers as innovative materials for high-

performance supercapacitors, utilizing magnetic field-assisted charge transport to improve energy storage efficiency[107]

SAHOO, A. et.al highlight the successful fabrication and electrochemical evaluation of $\text{ZrCoFe}_2\text{O}_4/\text{NRGO}$ nanocomposites as promising electrode materials for supercapacitor applications. The structural characterization confirmed the porous nature and nanoscale dimensions of the synthesized materials, with $\text{ZrCoFe}_2\text{O}_4/\text{NRGO}$ exhibiting enhanced properties. The electrochemical analysis demonstrated that the $\text{ZrCoFe}_2\text{O}_4/\text{NRGO}$ electrode achieved a high specific capacitance of 307 F g^{-1} at 1 A g^{-1} , along with excellent cycling stability, retaining 97% of its initial capacity after 5000 cycles. Furthermore, the asymmetric supercapacitor device utilizing $\text{ZrCoFe}_2\text{O}_4/\text{NRGO} // \text{NRGO}$ electrodes exhibited a specific capacitance of 137 F g^{-1} , an energy density of 42.7 Wh kg^{-1} , and a power density of 618.5 W kg^{-1} , reinforcing its potential for high-performance energy storage applications. These findings suggest that $\text{ZrCoFe}_2\text{O}_4/\text{NRGO}$ is a viable electrode material for next-generation supercapacitors, offering both high efficiency and long-term stability [108].

Martins, V. H..al demonstrate the successful preparation of reduced graphene oxide/polyaniline/iron oxide ternary composites as flexible, free-standing thin films using a simple doctor blade technique. The incorporation of polyaniline played a crucial role in eliminating the need for binders and conductive additives while enhancing the films' energy storage properties. The optimized composite achieved a specific capacitance of 281 F g^{-1} in a three-electrode system and 24 F g^{-1} in an all-solid supercapacitor, exhibiting strong long-term stability with 76% retention and excellent Coulombic efficiency between 92% and 166% after 3000 cycles at 3 A g^{-1} . Given that the fabrication method aligns with those used in commercial supercapacitors, these ternary free-standing films present a promising pathway for large-scale application in energy storage systems[109].

Sharma, P., Ahmad, S. et al successfully synthesized the ternary composite $\text{GO/PANI/CoFe}_2\text{O}_4$ using the oxidative polymerization method, and have demonstrated its potential as a high-performance electrode material for supercapacitor applications. Structural and morphological characterizations confirmed the formation of the hybrid

material, while electrochemical evaluations revealed outstanding performance. The composite exhibited a high specific capacitance of 781.27 F/g in a three-electrode system and 346.92 F/g in a symmetric two-electrode device, along with a wide potential window of 1.2 V. Additionally, it delivered a high specific energy of 69.38 Wh/kg at 1 A/g and a specific power of 5989.37 W/kg at 20 A/g, with 79.03% capacitance retention after 5000 cycles. The low charge transfer resistance (R_{ct}) of 8.51 Ω further highlights its efficient electrochemical behavior. The remarkable performance of GO/PANI/CoFe₂O₄ is attributed to the synergistic effect of its components, reinforcing its suitability for next-generation energy storage systems [110].

Gupta, M., Tyagi, S, et al. successfully synthesized the MnFe₂O₄/PEDOT/rGO ternary nanocomposite using the hydrothermal method and have demonstrated its potential as an efficient electrode material for supercapacitor applications. The in situ incorporation of MnFe₂O₄ within PEDOT layers on rGO has significantly improved ion transport by creating well-connected pathways, effectively reducing the resistance of bare ferrite by three orders of magnitude. This enhanced conductivity facilitates better charge transfer and storage, contributing to the improved electrochemical performance of the composite. Electrochemical characterization confirmed that the material exhibits a combination of EDLC and pseudocapacitive behavior, with a notable specific capacitance of 298.97 F g⁻¹ at a current density of 1 A g⁻¹ and 325 F g⁻¹ at a scan rate of 2 mVs⁻¹. Additionally, its ability to retain 81% of its initial capacitance over 5000 charge-discharge cycles highlights its excellent long-term electrochemical stability. Even at a high current density of 10 A g⁻¹, the nanocomposite maintained a capacitance of 87 F g⁻¹, further demonstrating its capability to operate efficiently under high-power conditions. The synergistic effect of Mn²⁺ and Fe³⁺ ions, as confirmed by X-ray photoelectron spectroscopy, plays a crucial role in optimizing the charge storage mechanism, contributing to the composite's superior energy storage properties. These findings suggest that the MnFe₂O₄/PEDOT/rGO nanocomposite, with its improved ion transport, high stability, and enhanced capacitance, holds strong potential for future supercapacitor applications, making it a viable candidate for next-generation energy storage devices[111].

Chee W.K. et al. synthesized ternary polypyrrole/graphene oxide/zinc oxide

supercapacitor electrodes and conducted a thorough evaluation of their electrochemical performance. They measured the gravimetric capacitance of the synthesized electrodes using a two-electrode system and determined it to be 94.6 Fg^{-1} at a current density of 1 Ag^{-1} based on charge/discharge (CD) curves. This study highlighted the potential of incorporating multiple materials to enhance supercapacitor performance[112].

Lim Y.S. et al. investigated a ternary composite consisting of polypyrrole, graphene, and nanomanganese oxide. Their findings revealed that the gravimetric capacitance of this composite was significantly higher than its components. Specifically, the ternary polypyrrole/graphene/nano manganese oxide composite exhibited a gravimetric capacitance of 320.6 Fg^{-1} at a scan rate of 1 mVs^{-1} . For comparison, the binary polypyrrole/graphene composite delivered a capacitance of 255.1 Fg^{-1} , while neat polypyrrole alone demonstrated a much lower capacitance of 118.4 Fg^{-1} . These results underscore the advantages of incorporating multiple active materials into the electrode composition to achieve superior energy storage capabilities[113].

Xiong P. et al. employed a three-electrode system to assess the electrochemical properties of ternary cobalt ferrite/graphene/polyaniline nanocomposites. Their investigation demonstrated that this composite material achieved an impressive gravimetric capacitance of 1133.3 Fg^{-1} at a scan rate of 1 mVs^{-1} . The significantly enhanced capacitance of this ternary nanocomposite further reinforced the notion that integrating multiple active materials can lead to substantial improvements in charge storage efficiency. Collectively, these studies provide compelling evidence that designing multi-component composite electrodes for supercapacitors is a highly effective and promising strategy. The incorporation of different functional materials within a single electrode structure enables a synergistic effect, leading to remarkable improvements in electrochemical performance. Such an approach holds great potential for advancing the development of high-performance supercapacitors, offering enhanced energy storage capabilities and improved stability for a wide range of applications[114].

Meng F. et al. (2019) reported that a hydrothermal reaction was utilized to synthesize a nickel-cobalt oxide/reduced graphene oxide ($\text{NiCo}_2\text{O}_4/\text{rGO}$) composite. The electrochemical performance of this material was evaluated, and at a current density of

0.5 A g⁻¹, it exhibited a specific capacitance of 702 F g⁻¹. This finding demonstrated the effectiveness of combining NiCo₂O₄ with rGO to enhance charge storage capacity and improve electrochemical properties[115].

Chandel et al. (2018) investigated the electrochemical performance of CuFe₂O₄-rGO nanocomposites. Their study revealed that these nanoparticles exhibited a specific capacitance of 797 F g⁻¹ when tested at a current density of 2 A g⁻¹. Additionally, after undergoing 2000 charge-discharge cycles, the material retained 91% of its initial capacitance, indicating a relatively moderate capacity fade of 9% over prolonged cycling[116].

Soam et al. (2019) recently examined the electrochemical behavior of an rGO-NiFe₂O₄ nanocomposite, which demonstrated a specific capacitance of 207 F g⁻¹. The study further highlighted that this composite retained an impressive 95% of its capacitance even after 1000 charge-discharge cycles, signifying its excellent stability and suitability for long-term applications in energy storage[117].

Cai, Y.Z. et al. (2018) researched a graphene-based hybrid material containing 30 wt% NiFe₂O₄. Their findings indicated that this hybrid composite achieved a specific capacitance of 210.9 F g⁻¹ while exhibiting remarkable cyclic stability. Even after 5000 charge-discharge cycles, the composite did not show any noticeable capacity degradation, and its retention improved when tested at a current density of 0.5 A g⁻¹. This suggested that the hybrid material was highly stable and had excellent potential for supercapacitor applications[118].

Chandel (2018) conducted an in-depth study on the electrochemical performance of CuFe₂O₄-rGO composites and reported that a composition consisting of 96% CuFe₂O₄ and 4% reduced graphene oxide demonstrated superior supercapacitor performance compared to pure CuFe₂O₄. The study revealed that this optimized composite exhibited a specific capacitance of 797 F g⁻¹ when tested at a current density of 2 A g⁻¹. Furthermore, after undergoing 2000 charge-discharge cycles, the material retained 91% of its initial capacitance, indicating a capacitance fade of only 9% over prolonged cycling. This result highlights the effectiveness of incorporating rGO into CuFe₂O₄ to enhance the electrochemical properties of the material[119].

Samal (2018) also investigated high-performance electrode materials for supercapacitors and reported that a specific composite, designated as WG-80, displayed a remarkably high capacitance value of 801.6 F/g at a current density of 4 A/g. The study further noted that the capacitance of reduced graphene oxide alone was measured to be 71.11 F/g, whereas tungsten trioxide (WO_3) exhibited a slightly higher specific capacitance of 94.22 F/g. However, the WG-80 composite demonstrated significantly superior electrochemical performance, surpassing the individual contributions of rGO and WO_3 . Additionally, throughout 5000 charge-discharge cycles, the composite maintained a strong cycling stability of 75.7%, confirming its potential as a durable and efficient electrode material for energy storage applications[120].

Deyab (2022) explored the electrochemical properties of rGO-NiFe₂O₄ nanocomposites and reported a significant improvement in specific capacitance. The study found that this nanocomposite exhibited a capacitance of 845 F/g, which was 3.2 times higher than that of pure NiFe₂O₄, which had a specific capacitance of only 264 F/g. This substantial enhancement in charge storage capacity demonstrated the synergistic effect of incorporating rGO with NiFe₂O₄, leading to improved electrochemical performance. Additionally, the rGO-NiFe₂O₄ composite displayed excellent cyclic stability, retaining 94.3% of its initial capacitance even after 5000 charge-discharge cycles. Furthermore, the device incorporating this composite exhibited a high power density of 620 W kg⁻¹ and an impressive energy density of 30.8 Wh kg⁻¹ when tested at a current density of 1.0 A g⁻¹. These findings further emphasized the potential of rGO-NiFe₂O₄ as a highly efficient electrode material for next-generation supercapacitor applications. Overall, these studies highlight the importance of developing hybrid nanocomposites by combining transition metal oxides with graphene-based materials. The results consistently demonstrate that such combinations lead to substantial improvements in specific capacitance, energy density, power density, and long-term stability. These advancements reinforce the potential of multi-component composite materials in the field of energy storage, paving the way for more efficient and durable supercapacitor technologies. To enhance the capacitive performance of NiFe₂O₄(NFO) and SrFe₁₂O₁₉ (SFO) based magnetically ordered pseudocapacitor electrodes by optimizing nanomaterial preparation techniques. The incorporation of biomimetic dispersing agents, high- energy ball milling, and n-doped conducting

polypyrrole composites significantly influenced capacitance performance. This Project applied the optimized GCD and HEBM parameters to SFO, yielding an improved capacitive response. Further enhancement was achieved by forming composites with Tiron-doped PPy, where varying mass ratios were explored to determine the most effective composition. The optimized SFO electrode was subsequently used as an anode in an aqueous asymmetric electrochemical capacitor with MnO_2 as the cathode. The assembled device demonstrated promising performance, highlighting the feasibility of the proposed electrode materials for practical energy storage applications. Overall, this research provides valuable insights into the impact of nanomaterial synthesis techniques on the electrochemical properties of magnetically ordered pseudocapacitor electrodes. The findings contribute to the advancement of high-performance capacitors and their potential use in a range of energy storage applications[121].

Ur Rehman, Z., et al. successfully developed (LSCM)/graphene oxide (GO) composite electrodes for energy storage applications. LSCM was synthesized using the solution combustion method, while GO was prepared through the improved Hummers' method. Composite dispersions of LSCM and GO were formulated using vacuum centrifuge mixing (VCM) and coated onto porous Ni foam to evaluate the effect of GO content on the specific capacitance (C_{sp}) of LSCM-based electrodes. Electrochemical characterization revealed that the pure LSCM electrode exhibited a maximum C_{sp} of 751 F/g at a scan rate of 1 mVs^{-1} . The incorporation of GO significantly enhanced the capacitance, with the highest C_{sp} of 1223 F/g obtained at a 5 wt% GO content. Cyclic voltammetry (CV) analysis confirmed the Faradic nature of charge storage, as evident from the distinct redox peaks. Electrochemical impedance spectroscopy (EIS) results demonstrated that the LSCM-5%GO electrode exhibited the lowest solution resistance, minimal charge transfer resistance, and the highest double-layer capacitance among all tested compositions. Furthermore, the optimized electrode composition retained 93% of its initial charge storage capacity after 3000 charge-discharge cycles, demonstrating excellent cycling stability. Overall, this research highlights the significant role of graphene oxide (GO) incorporation in enhancing the electrochemical performance of LSCM-based electrodes. The findings provide valuable insights into designing high-performance pseudocapacitive materials for advanced energy storage applications. This study successfully demonstrated the enhancement of electrochemical performance

in metal oxide-based supercapacitors through rare-earth element doping. A Lanthanum (La)-doped Nickel-tin oxide/reduced graphene oxide (LNSRG) composite was synthesized via a one-step hydrothermal method, with the optimized LNSRG 2 composite exhibiting a high specific capacitance of approximately 1238 F/g at a current density of 3 A/g in a 6 M KOH electrolyte. The impact of electrolyte pH on electrochemical behavior was systematically analyzed using different electrolytes. Furthermore, an asymmetric supercapacitor (ASC) was fabricated using LNSRG 2 as the positive electrode and sonochemically reduced graphene oxide (SRGO) as the negative electrode. The device achieved an energy density of about 38 W h kg⁻¹ at a power density of approximately 870 W kg⁻¹ within a 1.6 V potential window using 1 M Na₂SO₄ as the electrolyte. Notably, the ASC device retained around 75% of its initial capacitance even after 10,000 continuous charge-discharge cycles at a high current density of 15 A g⁻¹, demonstrating excellent cycling stability. Additionally, two ASC devices connected in series successfully powered a 1.8 V red LED, further showcasing their practical application potential. These findings highlight the effectiveness of rare-earth element doping in improving the electrochemical properties of metal oxide-based supercapacitors, paving the way for their use in advanced energy storage systems [122].

Samuel, E. et al. noted that nickel-iron (Ni-Fe)-based composites have attracted considerable interest because of their wide potential windows and improved electrochemical performance, rendering them particularly appropriate for supercapacitor (SC) electrode applications. This study introduces a straightforward synthesis method for creating beehive-like NiFe₂O₄ nanosheets that are directly grown on Ni nanocones, intended for application as supercapacitor electrodes. The synthesis process incorporates electrodeposition, facilitating the creation of ultrathin nanosheets characterized by a highly porous structure. This design results in a significant enhancement of the electrode-electrolyte interface, which improves charge transfer kinetics and elevates electrochemical performance. Through a methodical approach to varying the electrodeposition duration, the team successfully optimized the density of energy storage sites and refined the structural cavities to enhance efficient ion diffusion. The integration of structured cavities with active sites plays a crucial role in the exceptional electrochemical stability of the material, evidenced by a notable capacitance retention of 95.3% following 10,000 charge-discharge cycles. Furthermore, the

electrochemical performance testing demonstrated that these NiFe_2O_4 nanosheets possess a remarkable specific capacitance of 483 F/g at a current density of 5 A/g, highlighting their outstanding charge storage capabilities and excellent pseudocapacitive behavior. The findings emphasize the combined advantages of the nanosheet architecture and the Ni nanocone base, which together enhance conductivity, facilitate ion diffusion pathways, and boost overall energy storage efficiency. This investigation highlights the capabilities of beehive-like NiFe_2O_4 nanosheets as innovative electrode materials for supercapacitors, presenting a compelling blend of high capacitance, prolonged cycling stability, and enhanced charge transport. The results underscore the significance of structural engineering and material hybridization in the progression of next-generation energy storage technologies, setting the stage for scalable, high-performance supercapacitor applications [123].

Ko, T. H., and Lei, D., explored electrochemical assessment of polypyrrole (PPy) layer-coated NiCo_2O_4 -decorated carbon fiber paper (PPy- NiCo_2O_4 @CFP) composites, developed through a sequential two-step method aimed at improving their electrochemical performance for energy storage applications. The creation of these composites focuses on enhancing charge storage capacity, electrical conductivity, and structural stability, positioning them as highly promising candidates for next-generation supercapacitor devices. Initially, hierarchical NiCo_2O_4 -decorated CFP (NiCo_2O_4 @CFP) was synthesized using a low-temperature hydrothermal method. This approach facilitated the creation of a strong and conductive backbone, characterized by a high surface area, which is essential for efficient charge storage. This step led to the consistent development of NiCo_2O_4 nanostructures on the carbon fiber paper substrate, forming a cohesive system that promotes improved electrochemical activity. In the second step, a PPy layer was electrochemically deposited onto the NiCo_2O_4 @CFP composites by sweeping the potential between 0.2 and 1.0 V at a scan rate of 50 mV/s across multiple electrodeposition cycles (0, 5, 10, 15, and 20 cycles) in the presence of a pyrrole monomer. The SEM analysis validated the uniform growth of NiCo_2O_4 nanostructures on CFP, along with the stratified deposition of PPy, which significantly influenced the surface morphology and electrochemical characteristics of the composites. The investigation rigorously examined how different numbers of electrodeposition cycles influence the electrochemical behavior of the PPy-

NiCo₂O₄@CFP composites. Among the various composites synthesized, the one featuring 15 cycles of electrodeposited PPy (PPy15-NiCo₂O₄@CFP) exhibited the most impressive electrochemical performance, reaching a maximum specific capacitance of around 239 F/g at a current density of 2 A/g. Furthermore, this enhanced composite demonstrated a remarkable energy density of 64.95 Wh kg⁻¹ at a power density of 1400.2 W kg⁻¹, underscoring its potential for high-power energy storage applications. The outstanding electrochemical performance of the PPy15-NiCo₂O₄@CFP composite can be ascribed to the synergistic interactions among its essential components. The conductive PPy layer significantly improves charge transport, and the high-surface-area NiCo₂O₄ nanostructures offer numerous active sites for redox reactions. In the interim, carbon fiber paper (CFP) functions as an effective conductive network, facilitating rapid electron transfer and providing mechanical stability. The results highlight the promise of PPy-NiCo₂O₄@CFP composites as effective electrode materials for supercapacitor applications, underscoring their significance in the advancement of sophisticated energy storage solutions. This study offers important insights into strategies for material hybridization that can greatly enhance energy storage efficiency, cycling stability, and power density, positioning these composites as strong candidates for future electrochemical energy storage systems [124].

Reddy, N. R. et al. synthesized Cu-CdFe/g catalyst through a combination of hydrothermal and wet impregnation methods, yielding a material with outstanding electrochemical properties. This synthesis method achieved a consistent distribution of active components and created a highly porous structure, leading to a notable improvement in the catalyst's charge storage capacity and electrochemical performance. The electrochemical characterization demonstrated that the Cu-CdFe/g catalyst achieved an impressive specific capacitance of 1067 F/g at a current density of 0.25 A/g, underscoring its exceptional capability to store and deliver charge effectively. The exceptional performance can be ascribed to the synergistic interactions among Cu, Cd, and Fe, which lead to increased conductivity, enhanced redox activity, and effective ion diffusion within the electrode material. Additionally, when integrated into an asymmetric supercapacitor device setup, the Cu-CdFe/g catalyst exhibited robust electrochemical performance, reaching a specific capacitance of 140 F/g at a current density of 0.5 A/g. This finding highlights the material's capability for high-power

energy storage applications, showcasing its adaptability and reliability in real-world operating conditions. The integration of elevated specific capacitance, advantageous charge transport characteristics, and remarkable electrochemical stability positions the Cu-CdFe/g catalyst as a highly promising option for the advancement of supercapacitor technologies in the future. The performance observed in an asymmetric device underscores its potential for scalable, high-performance energy storage solutions, positioning it as a significant material for advanced energy storage applications [125].

2.3 Objectives of the Study

The objectives of this research are:

- Synthesis and characterization of polypyrrole, rGO, Ni-Sr ferrite.
- Investigation of electrochemical properties of rGO/Ni-Sr ferrite and polypyrrole/Ni-Sr ferrite electrode for energy storage applications.
- Electrochemical study of polypyrrole/rGO/Ni-Sr ferrite electrodes for energy storage applications.

2.4 Conclusion:

Metal ferrites have demonstrated significant potential as materials for supercapacitor applications due to their favorable properties, including high electrical conductivity, cost-effectiveness, optical performance, and electrochemical efficiency. However, their standalone electrochemical performance has certain limitations, which researchers have addressed by incorporating other materials to form nanocomposites. This approach has been shown to enhance the electrochemical properties of pristine metal ferrites, making them more viable for energy storage applications. In this chapter, we explored recent research on Mn, Co, Cu, Sr and Ni ferrites, emphasizing their synthesis methods and the impact of these processes on their electrochemical behavior. Different characterization techniques were also discussed, providing insights into the morphological, structural, electrical, and electrochemical properties of these nanoferrites. The positive attributes observed in these studies further reinforce the suitability of metal ferrites for supercapacitor applications, particularly when used in composite form. The continuous development of synthesis techniques and material enhancements will likely lead to further advancements in this field, optimizing their performance for next-generation energy storage systems. The advancement of

supercapacitor electrodes has historically focused on metal oxides and, conducting polymers both of which are esteemed for their extensive redox electrochemistry and capacity to enable high-capacity charge storage. The extensive study of these materials highlights their potential to improve the energy density of supercapacitors, positioning them as promising candidates for future energy storage systems. Nonetheless, in spite of their benefits, these materials face a number of significant challenges that restrict their broader use. A significant concern is the structural instability resulting from shape alterations during charge-discharge cycles, which ultimately leads to material degradation over time and undermines the overall lifespan of the electrode. Moreover, the low electronic conductance poses a considerable constraint, as it hinders the effective transport of charge carriers throughout the material. The measurement of conductance presents significant challenges owing to the highly porous characteristics of these electrodes, which complicate the acquisition of accurate and dependable conductivity data. Alongside these electrical and mechanical constraints, stability issues emerge from the inherent properties of the materials, potentially resulting in capacity degradation with extended usage. A variety of metal oxides and CPs exhibit limitations in charge storage capabilities, as their electrochemical properties may not achieve optimal energy retention and delivery efficiency. A significant limitation lies in the morphological constraints linked to these materials. The structural architectures frequently impede rapid ion transport, thereby diminishing the efficiency of charge-discharge cycles. The restricted access to electrochemically active surface areas significantly hinders electrochemical performance, as ions cannot completely engage with the available redox-active sites, resulting in a decrease in overall capacitance. The challenges underscore the necessity for innovative material designs and hybrid electrode architectures that can address these limitations, providing improved conductivity, structural stability, and electrochemical efficiency for high-performance supercapacitor applications.

Chapter 3

(Materials and Methodology)

3.1 Materials

The study involved the use of reduced graphene oxide (rGO), Ni-SrFe₂O₄, PPy, and various other chemical compounds. Graphene oxide (GO) was subsequently synthesized and reduced to form rGO, ensuring improved electrical conductivity. GO is synthesized by oxidizing graphite using strong oxidizing agents such as sulfuric acid (H₂SO₄), potassium permanganate (KMnO₄), and sodium nitrate (NaNO₃). The synthesis of Ni-SrFe₂O₄ was carried out using high-purity nickel nitrate, strontium nitrate, and iron nitrate, which served as precursor materials. Pyrrole monomers were utilized for the polymerization of PPy, while citric acid acted as a fuel agent in the sol-gel process. Ammonium hydroxide (NH₃) was employed for pH adjustment, and FeCl₃ functioned as an oxidizing agent for polypyrrole synthesis. Deionized (DI) water was used throughout all synthesis steps to maintain the purity of reactions. All chemicals were of analytical grade, sourced from Sigma-Aldrich with 99% purity, and used without further purification.

3.2 Introduction:

There are several methods available for the synthesis of ferrites, each offering unique advantages depending on the desired properties and applications of the final material. The most commonly used techniques include the sol-gel method, co-precipitation, hydrothermal synthesis, spray pyrolysis, and reverse micelle precursor methods. Every technique has its benefits. However, there is still a lot of interest in attempting to enhance the physical characteristics of ferrites by innovative synthesized designs. Ultrafine, uniform, and repeatable powders have recently been produced using sol-gel techniques. The chemical and physical properties of ferrites are significantly influenced by the synthesis technique and processing temperature. Among these, the hydrothermal method and the sol-gel auto-combustion technique are the most widely utilized for ferrite synthesis due to their ability to produce high-purity and well-crystallized nanoparticles with controlled morphology and phase composition. The hydrothermal method is one of the most effective and widely employed techniques for nanoparticle

synthesis. Compared to other methods, hydrothermal synthesis allows for precise control over particle size, crystallinity, and composition by adjusting temperature, pressure, reaction time, and precursor concentration. This method also facilitates the growth of well-defined, high-quality nanoparticles with minimal defects. Due to its versatility, the hydrothermal approach is commonly used in the preparation of ferrites for various applications, including magnetic, electronic, and electrochemical devices. Additionally, the co-precipitation technique is another widely used method for ferrite synthesis. It is a simple, cost-effective, and relatively time-efficient process that allows for large-scale production of nanoparticles. This method offers better control over particle size distribution and ensures a homogeneous elemental composition of the synthesized ferrites. For the first time, a comparative study was conducted to evaluate two different methods for the synthesis, characterization, and electrochemical analysis of pure cobalt and nickel ferrites. The study compared the co-precipitation technique followed by hydrothermal treatment with the direct hydrothermal approach. By analyzing these two distinct methods, the study provided valuable insights into the impact of synthesis techniques on the structural, morphological, and electrochemical properties of cobalt and nickel ferrites, paving the way for optimized material design in advanced applications. The sol-gel technique has recently been found to offer distinct advantages over traditional dry processing.

However, ferrite materials have been synthesized using a range of wet techniques, including ball milling, hydrothermal, sol-gel, microemulsions, and co-precipitation. The method chosen for the production of nano ferrites plays a crucial role in determining their structural, magnetic, and electrochemical characteristics. Various synthesis methods have been developed to tailor ferrite properties for specific applications. Nano ferrites can be synthesized using several techniques, each offering unique advantages in terms of particle size, crystallinity, and purity. These methods include solvothermal synthesis, microwave-hydrothermal synthesis, co-precipitation, the solid-state reaction approach, the sol-gel auto-combustion method, hydrothermal synthesis, and green synthesis. Additionally, molten salt techniques have been explored for ferrite production, offering efficient pathways for achieving high-phase purity and controlled morphology. The choice of synthesis method depends on the desired properties, such as magnetic behavior, electrical conductivity, and structural stability,

making ferrites highly versatile for various applications.

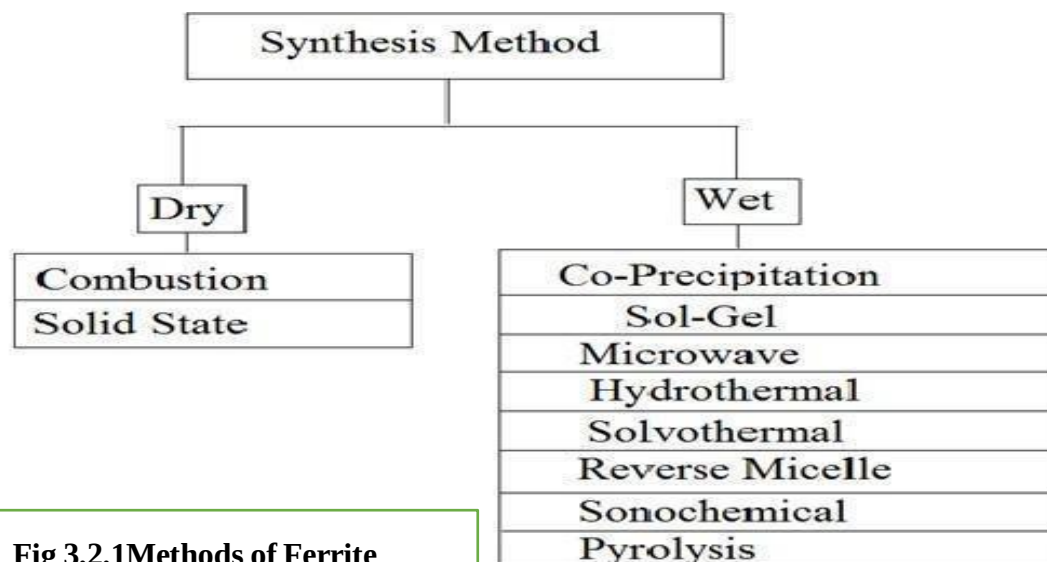


Fig 3.2.1 Methods of Ferrite synthesis

Ni-Sr ferrite was synthesized using the sol-gel auto-combustion method, a precise and efficient approach that allows for fine control over particle size, phase purity, and magnetic properties. This method ensures the formation of a homogeneous and well-crystallized ferrite structure, optimizing its performance for electrochemical and magnetic applications [126-130].

The synthesis of these materials follows well-established and optimized methods to ensure their structural integrity, stability, and electrochemical efficiency. PPy was synthesized through chemical oxidative polymerization, a widely used technique that ensures uniform conductivity, improved electrochemical activity, and better charge storage capacity. This process facilitates the formation of a highly conductive polymer network, which enhances its suitability for energy storage applications.

rGO was prepared using a modified Hummers method, which involves the oxidation of graphite to GO and then a controlled reduction process. This method effectively restores electrical conductivity while maintaining a high surface area, making rGO an ideal material for composite structures requiring enhanced charge transport and ion diffusion properties.

3.3 Synthesis of Polypyrrole (PPy)



Fig.3.3.1 Synthesis of Polypyrrole

To synthesize PPy, 0.5 M pyrrole (monomer) was prepared by adding 1.73 ml of pyrrole to 50 ml of distilled water. To this solution, a cationic surfactant, cetyltrimethylammonium bromide (CTAB), was introduced at a concentration of 0.025 M (0.455 g) to aid in the polymerization process. Separately, FeCl_3 , which acts as an oxidant, was dissolved in 50 mL of distilled water.

The polymerization process began by placing the pyrrole-surfactant solution on a magnetic stirrer, ensuring continuous mixing. The FeCl_3 solution was then added gradually using a burette, allowing controlled addition to prevent rapid oxidation, which could affect the polymer's properties. The reaction mixture was stirred for four hours at room temperature, allowing sufficient time for polymerization to take place. Once the polymerization was complete, the resulting PPy was separated by filtration, thoroughly washed with distilled water to remove any residual reagents or by-products, and then dried in an oven at 60°C for 12 hours to obtain a fine, dry powder. The final product appeared as a black-colored powder, characteristic of polypyrrole. A schematic representation of the experimental setup and procedure is provided in Fig.

3.3.2 to illustrate the synthesis process in detail.

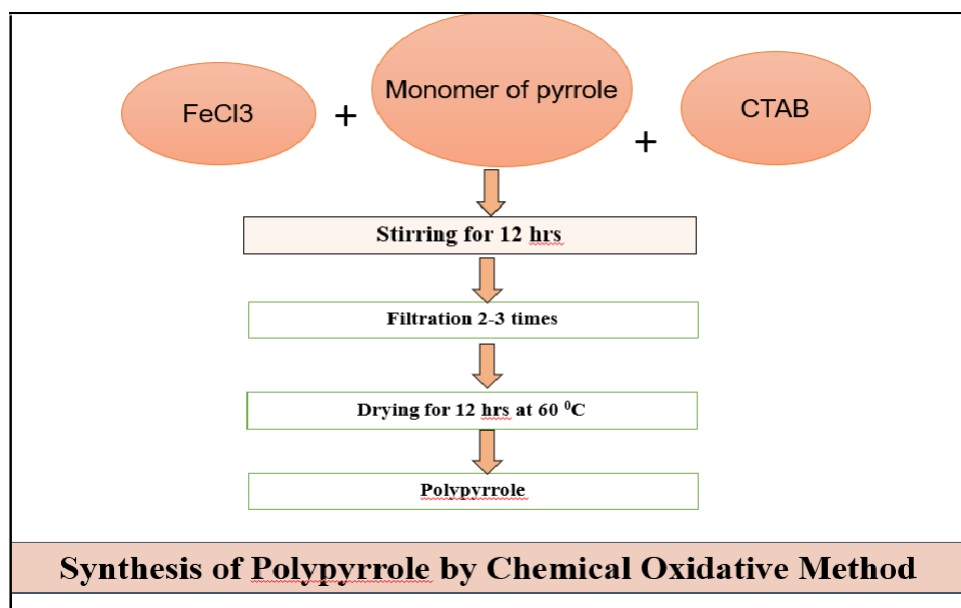


Fig. 3.3.2 Chemical Oxidative polymerization

Benefits of this Method:

- Ensures a high degree of polymerization with uniform morphology and conductivity.
- Facilitates easy incorporation with rGO and metal ferrites for hybrid electrode materials.
- Enhances pseudocapacitive charge storage due to its redox-active nature.

3.4 Synthesis of GO and rGO

The oxidation process introduces oxygen-containing functional groups, including hydroxyl (-OH) and epoxy (-O-) groups, onto the surface of graphene layers. These modifications enhance the hydrophilicity and dispersibility of graphene oxide, making it easier to process in aqueous solutions. The modified Hummers method is commonly employed to convert graphite into graphene oxide (GO) and subsequently into reduced graphene oxide (rGO).

The synthesis begins with taking 5 grams of finely powdered graphite and 150 mL of concentrated sulfuric acid (H_2SO_4) in a beaker. The mixture is stirred continuously for 30 minutes to ensure proper dispersion. While stirring, 7.5 grams of sodium nitrate (NaNO_3) is gradually added, which helps in the intercalation process. This step increases the distance between graphite layers, making them more accessible for oxidation. Next, 15 grams of potassium permanganate (KMnO_4) is slowly introduced into the mixture over 4-5 hours while maintaining the temperature at 40°C . The addition

of KMnO_4 results in the gradual darkening of the mixture due to the oxidation process. The mixture is then stirred continuously for an additional 3 hours while keeping the temperature below 20°C using an ice bath. This controlled temperature prevents excessive oxidation and minimizes the formation of undesirable byproducts. After completing the oxidation process, 500 mL of distilled water is carefully added to the reaction mixture. The temperature is gradually increased to approximately 95°C , allowing the reaction to proceed efficiently. At this stage, 10 mL of hydrogen peroxide (H_2O_2) is introduced into the mixture while stirring for 30 minutes. This step helps to neutralize excess permanganate and manganese dioxide (MnO_2), causing the color of the solution to change from deep brown to yellow, indicating the successful oxidation of graphite into graphene oxide. To remove residual metal ions and other impurities, the mixture is washed multiple times (4-5 cycles) with distilled water. During each wash, 10 mL of DI water is used to ensure the effective removal of any remaining contaminants. To stabilize the pH of the solution, ammonia (NH_3) is added gradually. After washing, the mixture is filtered and subjected to sonication for 7-8 hours to further exfoliate the graphene oxide sheets and ensure uniform dispersion. The resulting slurry is then dried in an oven, leaving behind solid GO powder. To rGO, a chemical reduction process is carried out using hydrazine monohydrate as a reducing agent. First, the GO powder is dissolved in 100 mL of distilled water and sonicated for 30 minutes to ensure uniform dispersion. The solution is then stirred continuously while adding 1 mL of hydrazine monohydrate, which serves as a reducing agent to remove the majority of oxygen-containing functional groups. The mixture is heated between 95 - 100°C for a few hours to complete the reduction process. This step restores some of the electrical conductivity lost during oxidation by reducing the oxygen groups, resulting in rGO with improved conductivity and stability.

The final rGO product obtained through this process exhibits enhanced electrical and structural properties, making it highly suitable for applications in energy storage, sensors, and composite materials.

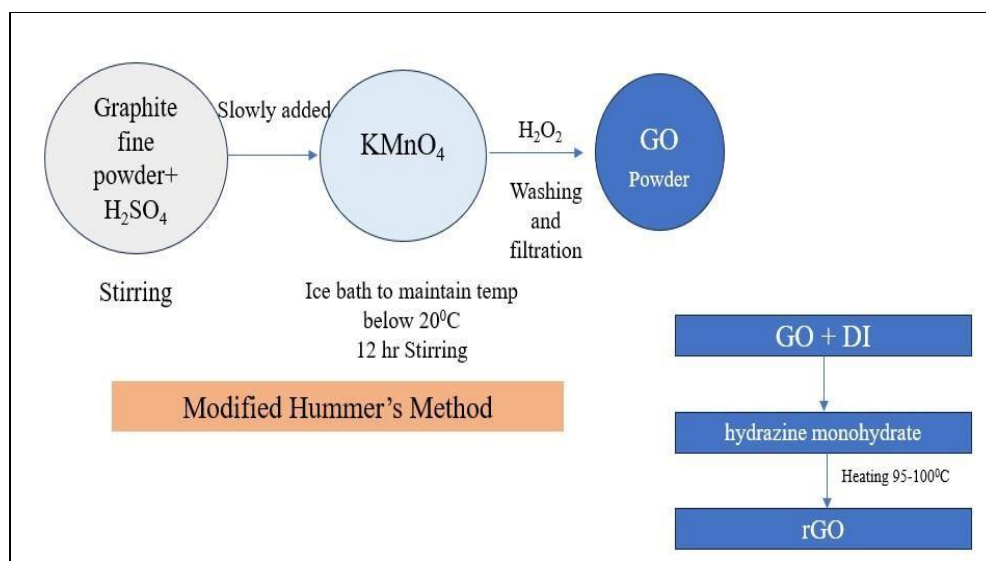


Fig. 3.4.1 Synthesis of GO and rGO by modified Hummer method

Benefits of this Method:

- Provides a scalable and cost-effective approach to synthesize rGO with controlled oxygen functional groups.
- Enhances the conductivity and electrochemical performance of rGO for energy storage applications.
- Improves dispersion ability in polymer and metal ferrite composites.

3.5 Synthesis of Ni-Sr ferrite

The synthesis of Ni-Sr ferrite was carried out using the sol-gel auto-combustion method, a widely recognized technique for producing nano-ferrites with high efficiency and precision. The sol-gel combustion process is considered one of the most straightforward and effective traditional methods for synthesizing nano-ferrites due to its ability to generate homogeneous, crystalline, and high-purity nanoparticles. This method is particularly advantageous because it enables the formation of ultrafine

particles with a narrow size distribution while requiring relatively short processing times and lower temperatures compared to other conventional techniques. Additionally, it provides excellent stoichiometric control, ensuring that the desired composition and phase purity are achieved. These attributes make the sol-gel auto-combustion method a highly attractive approach for synthesizing nanosized ferrite materials for various applications.

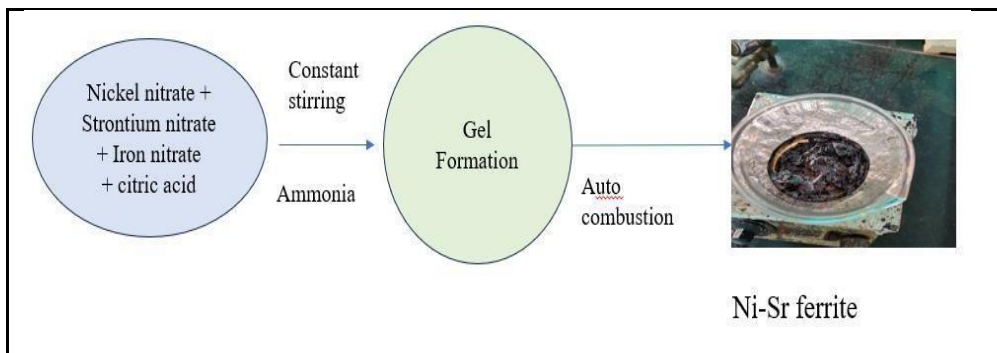


Fig. 3.4.2 Synthesis of Ni-Sr ferrite

This synthesis approach demonstrated superior stoichiometric control compared to standard methods, ensuring precise composition and enhanced material properties. The physical characteristics and morphology of the final product are significantly influenced by the synthesis process, making careful parameter optimization essential. By adjusting key synthesis factors such as gelation duration, reaction temperature, reagent concentration, and medium pH, the sol-gel process allows for fine-tuning of the material's physical properties. This flexibility makes it an effective and versatile technique for obtaining highly phase-pure and chemically homogeneous particles with well-defined grain morphology.

To begin the synthesis, 3M of nickel nitrate and 3M of strontium nitrate were dissolved in 150 mL of DI water in a beaker. To this solution, 6M of ferric nitrate was added in a precise molar ratio of 1:1:2 for Ni nitrate, Sr nitrate, and ferric nitrate, respectively. The

inclusion of citric acid as a fuel agent facilitated uniform mixing and promoted a stable sol-gel formation. Ammonia (NH_3) was carefully introduced to regulate the pH of the solution, adjusting it to a controlled range of 7–8, which is critical for preventing unwanted precipitation and ensuring a homogeneous reaction environment. Once the sol-gel formation was complete, the resulting composite was subjected to multiple rinsing cycles using DI water to remove any residual reactants, unreacted precursors, or impurities. In the final stage, the purified material was dried in an oven set to 80°C to eliminate moisture and improve structural integrity. This systematic and well-regulated approach successfully produced a high-purity Ni-Sr ferrite composite with tailored properties suitable for various applications, including magnetic and electrochemical devices.

3.6 Synthesis of binary composites

(a) rGO/Ni-SrFe₂O₄

The sol-gel method was employed to synthesize the binary composite rGO/Ni-SrFe₂O₄, ensuring a well-integrated and homogeneous material. The process began with the preparation of rGO, which was synthesized using the widely recognized Hummers method. This method involves the oxidation of graphite to graphene oxide, followed by a reduction step to obtain rGO with enhanced electrical conductivity and surface functionality. The incorporation of rGO into the composite plays a crucial role in improving its electrochemical performance and structural stability. To prepare the precursor solution for the sol-gel synthesis, 3M nickel nitrate, strontium nitrate, and iron nitrate were dissolved in 150 mL of DI water. These metal precursors ensured the formation of the Ni-SrFe₂O₄ phase within the composite. The pH of the solution was carefully adjusted to a range of 7-8 using ammonia to ensure optimal reaction conditions and prevent unwanted precipitation. To achieve proper dispersion and integration of rGO within the composite, the rGO suspension was subjected to multiple cycles of sonication. This step helped break up any agglomerates, allowing for a more uniform dispersion of rGO throughout the solution. Once well dispersed, the rGO was introduced into the metal precursor solution while maintaining a stable pH to prevent any unwanted reactions or phase separation. The temperature of the solution was gradually increased to $90\text{--}95^\circ\text{C}$, promoting the formation of a gel-like structure. As the

temperature increased, the sol transformed into a gel, ensuring uniform mixing of the metal ions and rGO. The gel was then carefully placed onto a hot plate and heated further until the desired composite material was obtained. Following the gelation process, the composite was thoroughly rinsed 3-4 times with DI water to remove any residual reactants and byproducts. Finally, the material was dried in an oven set to 80°C to remove residual moisture and enhance the structural integrity of the rGO/Ni-SrFe₂O₄ composite. This sol-gel synthesis method effectively incorporates rGO into the binary composite, resulting in a durable and functional material with enhanced properties suitable for a wide range of applications, including energy storage and electrochemical devices.

(b) Synthesis of PPy/Ni-SrFerrite

A chemical oxidative technique was employed to incorporate polypyrrole into Ni-SrFe₂O₄, ensuring an effective and uniform distribution of the polymer within the composite material. Both chemical oxidative polymerization and electrochemical deposition are commonly used techniques for synthesizing PPy. However, chemical oxidative polymerization remains one of the earliest, most widely used, and efficient methods for PPy synthesis due to its simplicity, scalability, and minimal equipment requirements. This method enables the rapid production of PPy without the need for complex setups, making it highly suitable for large-scale synthesis. Furthermore, PPy produced through this approach forms as an amorphous suspension that precipitates within the bulk polymerization solution, which further contributes to the practicality of this method for generating polymer composites.

The synthesis process began with the preparation of a homogeneous reaction mixture. Initially, 50 mL DI water was used as the solvent, into which Ni-SrFe₂O₄, cetyltrimethylammonium bromide (CTAB), and pyrrole monomers were added. The combination of these components was thoroughly mixed and agitated at room temperature to ensure uniform dispersion and interaction. The presence of CTAB, a surfactant, helps to stabilize the polymerization process and prevent uncontrolled aggregation of the monomers and polymeric chains.

To facilitate the polymerization of PPy, an oxidizing solution was prepared separately by dissolving ferric chloride (FeCl₃) in another 50 mL of DI water. FeCl₃ acts as the

oxidant, initiating and driving the polymerization of pyrrole monomers into polypyrrole. To ensure a controlled and efficient polymerization process, the FeCl_3 solution was gradually introduced into the monomer mixture. This slow and controlled addition helped prevent excessive nucleation and aggregation of PPy, ensuring that polymerization occurred in a well-regulated manner. Following the addition of the oxidant, the reaction mixture was subjected to continuous stirring for 12 hours at room temperature. The extended stirring period allowed for complete polymerization and uniform coating of $\text{Ni-SrFe}_2\text{O}_4$ particles with PPy, ensuring the successful formation of a well-integrated binary composite. After the polymerization was completed, the resulting mixture was carefully filtered multiple times to remove any residual reactants, unreacted monomers, and byproducts. The filtered composite was then thoroughly rinsed with DI water to eliminate any remaining impurities that might interfere with its electrochemical properties. The purified product was subsequently dried in an oven at 80°C , ensuring the removal of residual moisture and enhancing the structural stability of the PPy-incorporated composite. This drying process helped in achieving the desired consistency and composition of the final product.

By successfully incorporating PPy into $\text{Ni-SrFe}_2\text{O}_4$ through this method, the resulting composite exhibited improved electrochemical properties, enhanced conductivity, and better stability.

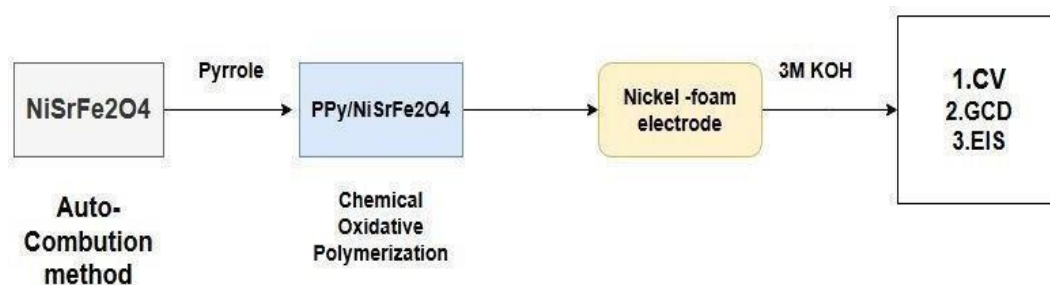


Fig. 3.6.1 Composite formation and Electrochemical Study

The prepared composite was further subjected to extensive characterization and

analysis to evaluate its electrochemical performance, making it a promising candidate for energy storage applications such as supercapacitors and advanced battery technologies.

3.7 Synthesis of ternary composite PPy/rGO/Ni-SrFe₂O₄ (PRNS)

A chemical oxidative approach was used to introduce PPy into the binary composite material. To initiate the polymerization of PPy, an oxidant solution was prepared by dissolving ferric chloride (FeCl₃) in 50 mL of DI water. To maintain controlled polymerization conditions and prevent rapid aggregation, the FeCl₃ solution was carefully and gradually injected into the monomer mixture. This slow addition facilitated uniform polymer growth while minimizing structural defects. To ensure complete polymerization, the reaction mixture was continuously stirred for 10-12 hours. This extended stirring duration allowed for thorough polymer formation, ensuring that PPy was well-integrated into the composite structure.

After polymerization, the reaction mixture went through 3 to 4 filtration steps to get rid of any leftover oxidants, monomers that didn't react, and byproducts. After filtering, the composite was thoroughly rinsed with DI water to get rid of any impurities that could affect how well it works as an electrochemical material. The purified product was then dried in an oven at 80°C to get rid of any extra moisture and make a stable, well-mixed PPy binary composite.

This carefully controlled synthesis method successfully adds PPy to the binary composite, making it more stable, conductive, and better at conducting electricity. The composite material that comes out of this process has better properties, which makes it perfect for energy storage, supercapacitors, and other advanced uses that need high conductivity and stability.

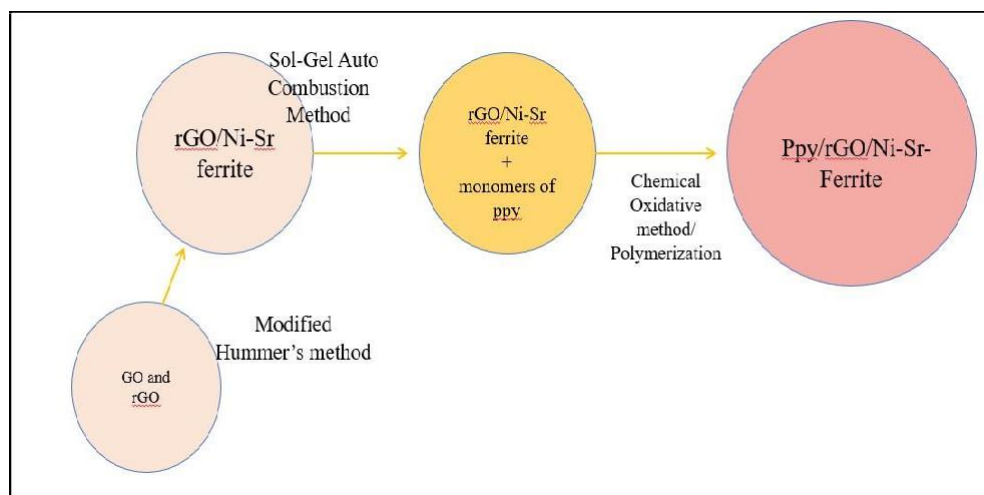


Fig.3.7.1 Synthesis of ternary composite

Using varying weight % of Ni and Sr from (0%-100%) doped with PPy/rGO/Fe₂O₄, this study aims to pave the way for the development of cutting-edge materials with higher performance, broadening the scope of potential energy storage applications by revealing the synergistic effects of reduced graphene oxide, polypyrrole, and Ni-Sr ferrite in electrodes.

3.8 Fabrication of Nickel foam electrode

Nickel foam is a widely used material for electrode substrates due to its unique properties. Here are its key characteristics:

1. Structural Properties

- **High Porosity:** allowing excellent electrolyte penetration and ion transport.
- **3D Network Structure:** Enhances electron conductivity and provides a large surface area for electrochemical reactions.
- **Lightweight:** Due to its porous structure, nickel foam has a low density, making it suitable for energy storage applications.

2. Electrical Properties

- High Electrical Conductivity: Essential for efficient electron transfer in electrochemical applications.
- Low Internal Resistance: Reduces energy loss in devices like batteries and supercapacitors.

3. Mechanical Properties

- High Strength and Toughness: Can endure repeated charge/discharge cycles without significant degradation.
- Good Flexibility: Can be easily shaped or compressed for different applications.

4. Electrochemical Properties

- Excellent Corrosion Resistance: Especially in alkaline environments, making it suitable for rechargeable batteries and fuel cells.
- Good Electrocatalytic Activity: Nickel foam is often used as a substrate for catalysts

5. Thermal Properties

- High Thermal Conductivity: Helps dissipate heat efficiently in high-power applications.
- Thermal Stability: Can withstand high temperatures, making it ideal for various electrochemical processes.

6. Chemical Compatibility

- Resistant to Oxidation in Alkaline Solutions: Ensures longevity in alkaline fuel cells and Ni-based batteries.
- Can Be Coated with Other Active Materials: Often used as a base for metal oxides or conducting polymers to enhance performance.

Applications in Electrodes

- Batteries (Ni-Cd, Li-ion, Zn-air)
- Supercapacitors
- Fuel Cells

- Electrocatalysis for Hydrogen Production
- Electrochemical Sensors [131]

To make the nickel foam electrode, the active material was put on the surface of a nickel foam substrate to make a working electrode that worked very well. The first step was to make a uniform slurry with 40 mg of active material composite, 5 mg of acetylene black to improve electrical conductivity, and 5 mg of polyvinylidene fluoride (PVDF) as a binder to keep the structure stable. The ratio of these parts was 8:1:1 to keep things consistent and improve adhesion. To get even dispersion and keep the right viscosity, 3 mL of N-methyl pyrrolidone (NMP) was added as a solvent. This made it easier to mix everything and apply it smoothly. After making the slurry, it was evenly spread over the nickel foam substrate to make sure that the porous structure was completely covered, which would improve the electrochemical performance. After that, the coated nickel foam was dried at 60°C to get rid of the solvent and help the composite material stick to the substrate better. Mechanical pressing was applied to the dried electrode to improve the contact between the active material and the current collector. This lowered internal resistance and made charge transfer more efficient. A three-electrode system was used to test the electrochemical performance. The working electrode was made of nickel foam with an active material coating. The reference electrode was an Ag/AgCl electrode, which kept the reference potential stable. The counter electrode was a platinum wire, which made the electrochemical setup strong and stable. 3M KOH was used as the electrolyte for all of our electrochemical measurements because it has a high ionic conductivity and works well with the electrode materials. Potassium hydroxide (KOH) is a common electrolyte in batteries, supercapacitors, and fuel cells, among other electrochemical applications. It stands out because of a few key benefits:

1. High Ionic Conductivity

- **Strong Electrolytic Nature:** KOH completely breaks down in water, releasing a lot of OH^- ions, which makes it easier for ions to move around.
- **Fast Charge Transfer:** The high mobility of OH^- ions makes ionic conduction happen quickly, which speeds up reaction kinetics in electrochemical devices.

2. Wide Electrochemical Stability Window

- **Stable in High Voltage Systems:** KOH enables a broad operating voltage range, which is crucial for high-energy applications.
- **Prevents Water Decomposition:** Compared to other alkaline electrolytes, KOH helps maintain stable electrode reactions.

3. Strong Alkaline Environment

- **Enhances Electrode Activity:** Many electrode materials, such as nickel-based and transition metal oxides, perform better in alkaline conditions.
- **Improves Redox Reactions:** KOH enables efficient electron transfer, critical for applications like fuel cells and supercapacitors.

4. High Chemical Stability & Compatibility

- **Non-Corrosive to Carbon Materials:** KOH is compatible with carbon-based electrodes (graphene, CNTs) used in supercapacitors.
- **Compatible with Metal Oxides:** Works well with metal oxides used in batteries and hybrid electrodes.

5. Thermal Stability & Safety

- **Stable at High Temperatures:**

KOH remains effective at elevated temperatures, making it suitable for high-power applications.

- **Non-Flammable in Aqueous Form:**

Compared to organic electrolytes, KOH-based electrolytes reduce the risk of thermal runaway.

6. Cost-Effectiveness & Availability

- **Inexpensive & Readily Available** KOH is cheaper than many other electrolytes, such as Li-based salts.

- **Easy to Handle & Prepare:** Can be diluted in different concentrations to optimize performance for specific applications[132].

The structural and morphological characterization of the fabricated electrode was performed using advanced analytical techniques. XRD analysis was conducted using a Bruker diffractometer to determine the crystalline structure and phase purity of the composite. The morphology and surface texture of the electrode were examined using a field emission scanning electron microscope (FESEM, ZIESS), providing insights into particle distribution, porosity, and surface roughness.

Additionally, Fourier-transform infrared spectroscopy (FTIR) was carried out using a Perkin Elmer spectrometer to identify functional groups and confirm the successful incorporation of polypyrrole, reduced graphene oxide, and Ni-Sr ferrite into the composite. Electrochemical studies were performed using a potentiostat to assess the charge storage capacity and energy storage efficiency of the fabricated electrode. CV was conducted at different scan rates to evaluate the capacitive behavior and charge-discharge kinetics of the electrode material. GCD analysis was carried out to determine the specific capacitance, energy density, and power density of the electrode, providing insights into its practical application for energy storage devices. EIS was employed to analyze charge transfer resistance and ion diffusion characteristics, which are critical factors influencing the electrode's overall performance. Active materials-coated nickel foam electrode exhibits a remarkable combination of high electrical conductivity, excellent electrochemical stability, and superior charge storage capacity, making it a promising candidate for advanced energy storage applications. Its well-structured composition ensures efficient charge transport and long-term stability, essential for high-performance supercapacitors. The systematic fabrication approach, coupled with comprehensive structural and electrochemical analysis, confirms the electrode's reliability and effectiveness. These characteristics validate its potential for next-generation energy storage technologies, where high power density, cyclic durability, and rapid charge-discharge capabilities are crucial for sustainable and efficient energy management solutions.

Chapter 4

Results and Discussions

4.1 Introduction

X-ray diffractography (XRD) is an effective method for figuring out a material's phase identity, crystalline structure, and crystallite size. In XRD, a material sample is exposed to X-rays, which, by Bragg's rule, diffract at particular angles. The crystal phases present in the sample are fingerprinted by the resulting diffraction pattern. Using the Scherrer equation, XRD may be used to estimate the average crystallite size in nanocomposites and determine the phase purity and crystallinity of the constituent materials. The samples were prepared and subjected to XRD using Bruker in the 2θ range from 10° to 90° . Morphology was examined using FESEM ZIESS. FESEM is used to see the surface morphology of materials at the nanoscale. FESEM produces high-resolution images that show the size, shape, and distribution of nanoparticles, nanocomposites, or thin films by scanning a concentrated electron beam over the sample. When analyzing the structural characteristics of electrode materials as their porosity, texture, and homogeneity—that are essential to their functionality in supercapacitors and other energy storage devices, SEM is especially helpful. A Perkin Elmer spectrometer was employed to carry out Fourier transform infrared spectroscopy (FTIR). FTIR is a method that measures a material's infrared absorption spectra in order to determine its functional groups and molecular bonds. In FTIR, infrared radiation is applied to the sample, and the absorption of particular wavelengths—which correspond to different vibrational modes of the chemical bonds, is recorded. When it comes to nanocomposites, FTIR can verify the existence of particular functional groups like hydroxyl, carbonyl, or metal-oxygen bonds, which are crucial for comprehending how the various components of the composite material interact with one another. FTIR plays a crucial role in evaluating the chemical environment and bonding structure of active materials in energy storage devices, which in turn impacts their electrochemical behavior. Assessing the effectiveness of electrode materials in energy storage devices such as supercapacitors requires electrochemical characterization. When evaluating the electrochemical characteristics of the materials, the following methods are frequently used: CV, GCD and EIS.

4.2 XRD Analysis

i) XRD of PPy and rGO

The synthesized PPy sample's X-ray diffraction (XRD) analysis shows a clear reflection peak at $2\theta = 25.2^\circ$, which is a sign of PPy's semi-crystalline structure. Polypyrrole usually shows a wide diffraction peak between 24° and 27° in 2θ , which is because it has an amorphous structure with some ordered polymer chains. This wide peak is caused by the regular arrangement of polymer backbones, which shows that conjugated π -electron systems are present in the polymer matrix. The (002) plane at rGO diffraction peak 25.2° indicating graphitic structure. This peak shows that GO has changed into rGO [70,71].

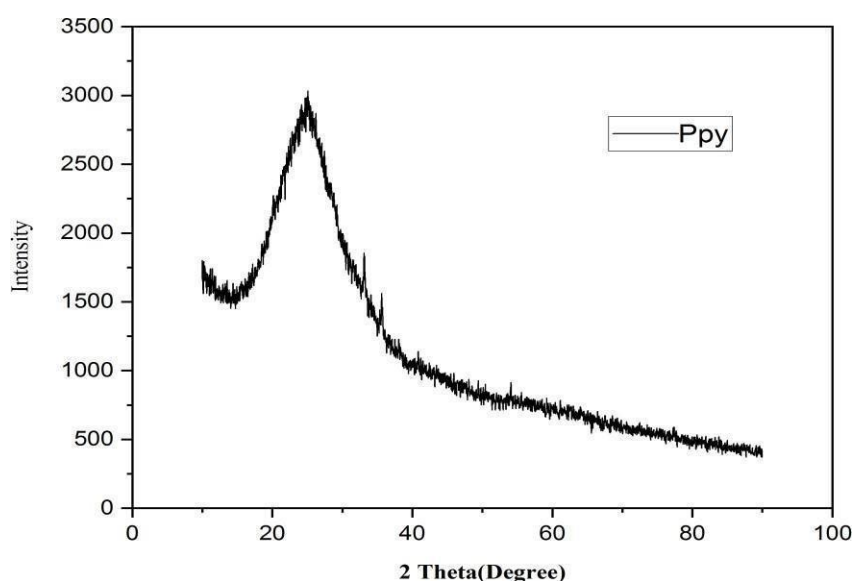


Fig. 4 .2.1 XRD spectrum of Polypyrrole

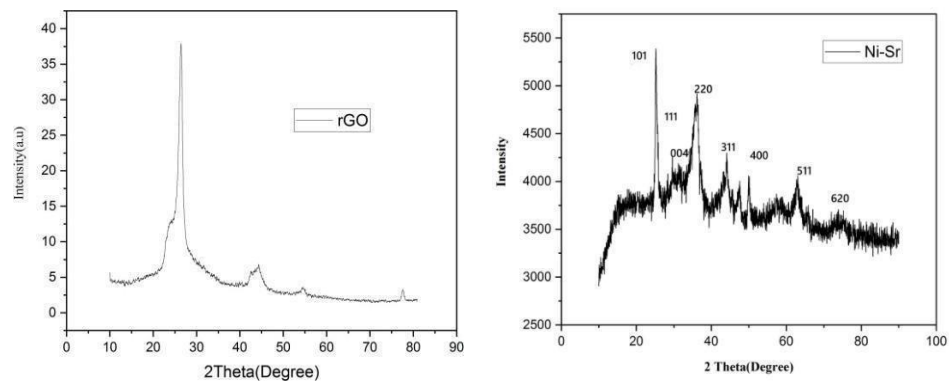


Fig.4.2.2 XRD spectrum of rGO and Ni-Sr Ferrite

ii) XRD of Binary and Ternary Composites

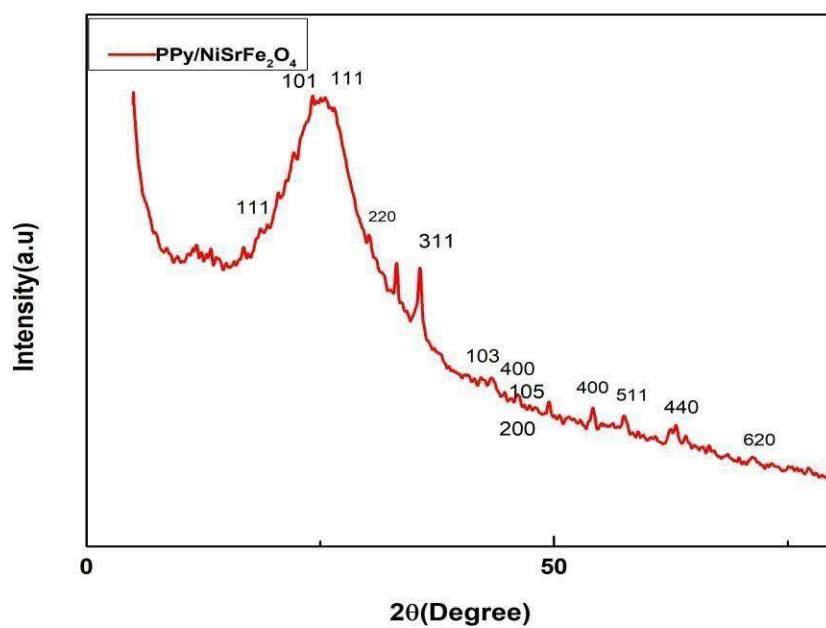


Fig.4.2.3 XRD of PPy/Ni-SrFe₂O₄

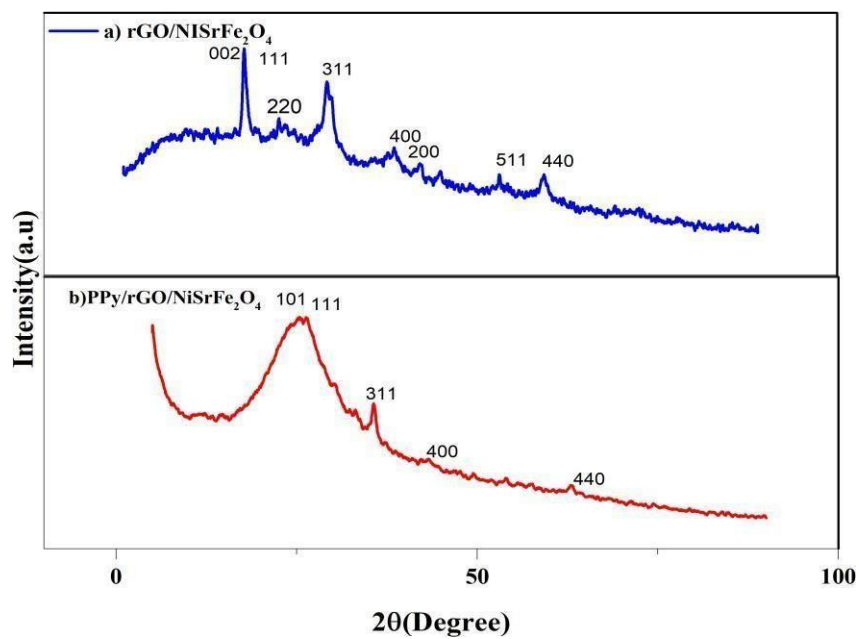


Fig. 4.2.4 XRD pattern of rGO/Ni-SrFe₂O₄ and PPy/rGO/Ni-SrFe₂O₄

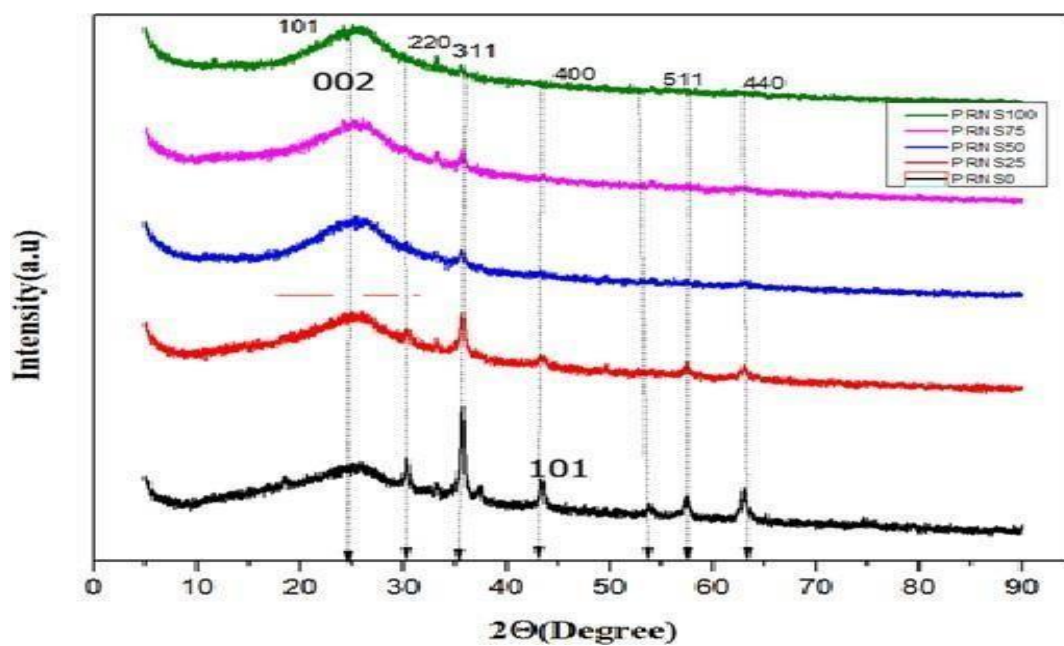


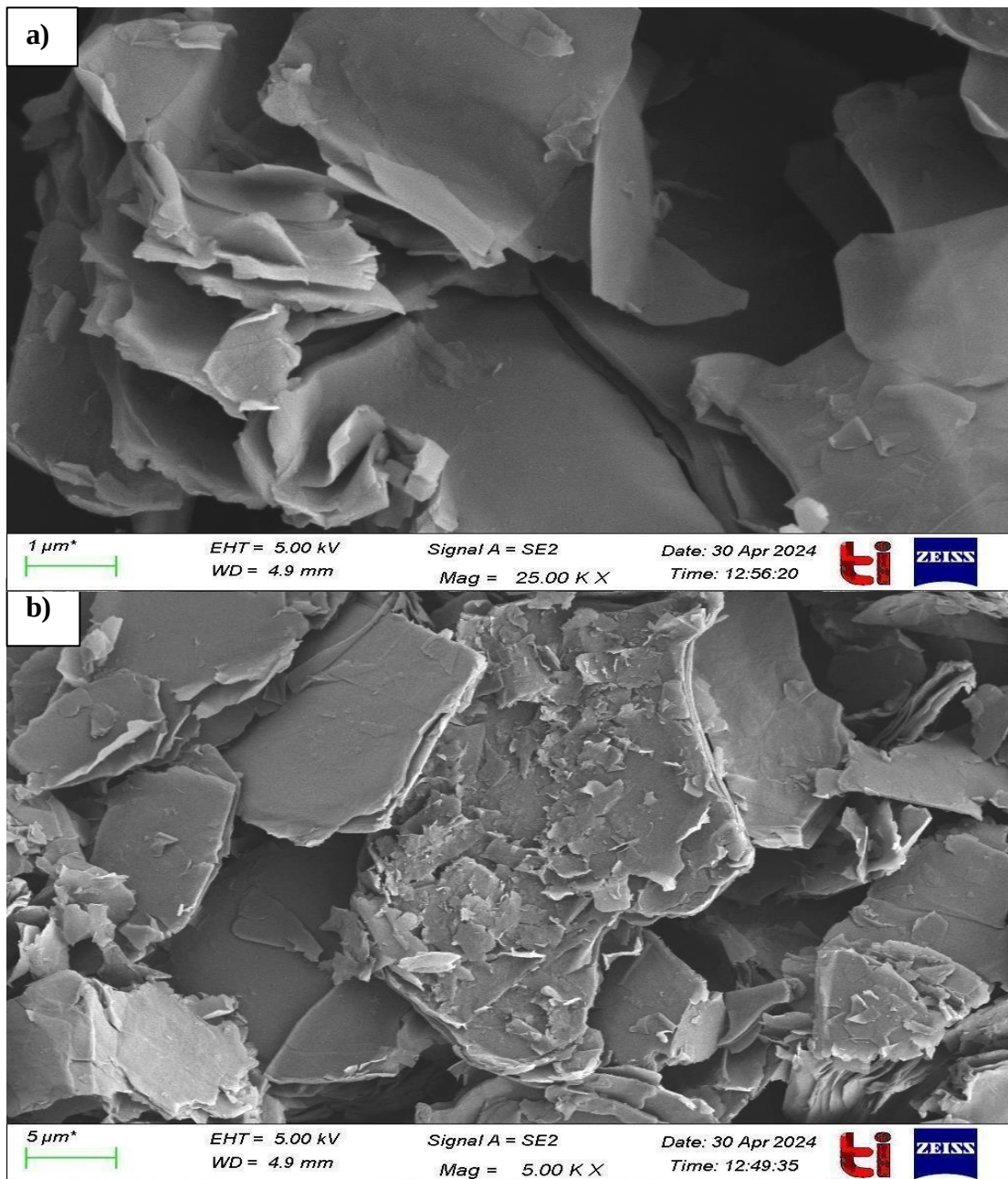
Fig.4.2.5 XRD of PPy/rGO/Ni-SrFe₂O₄ with varying weight percentage of nickel and strontium.

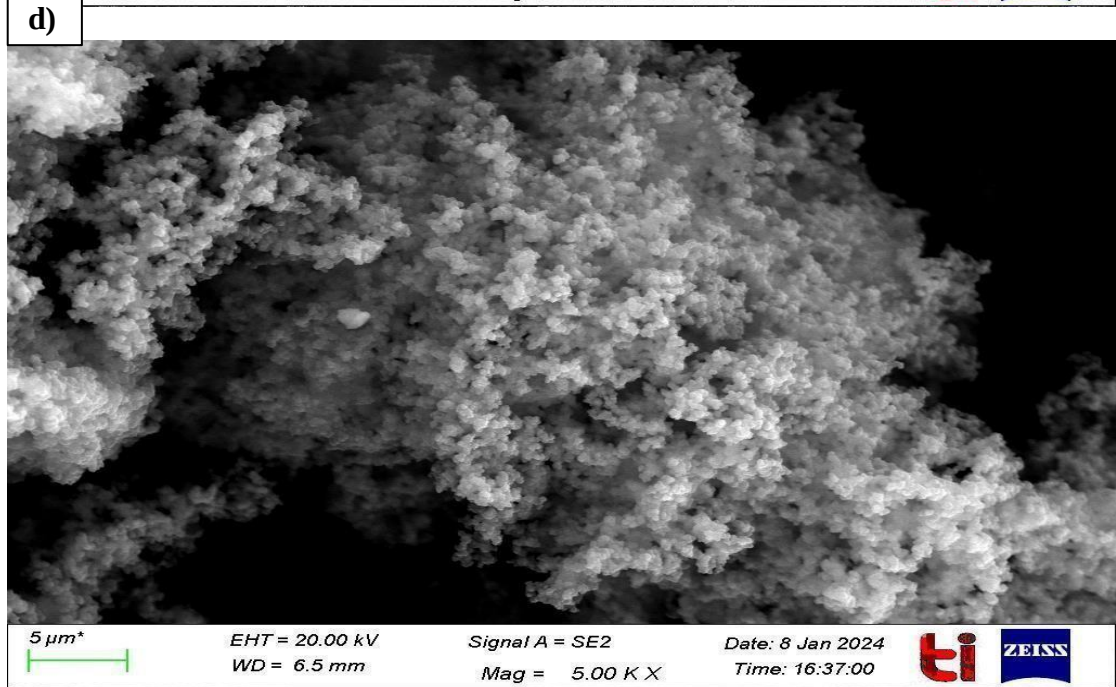
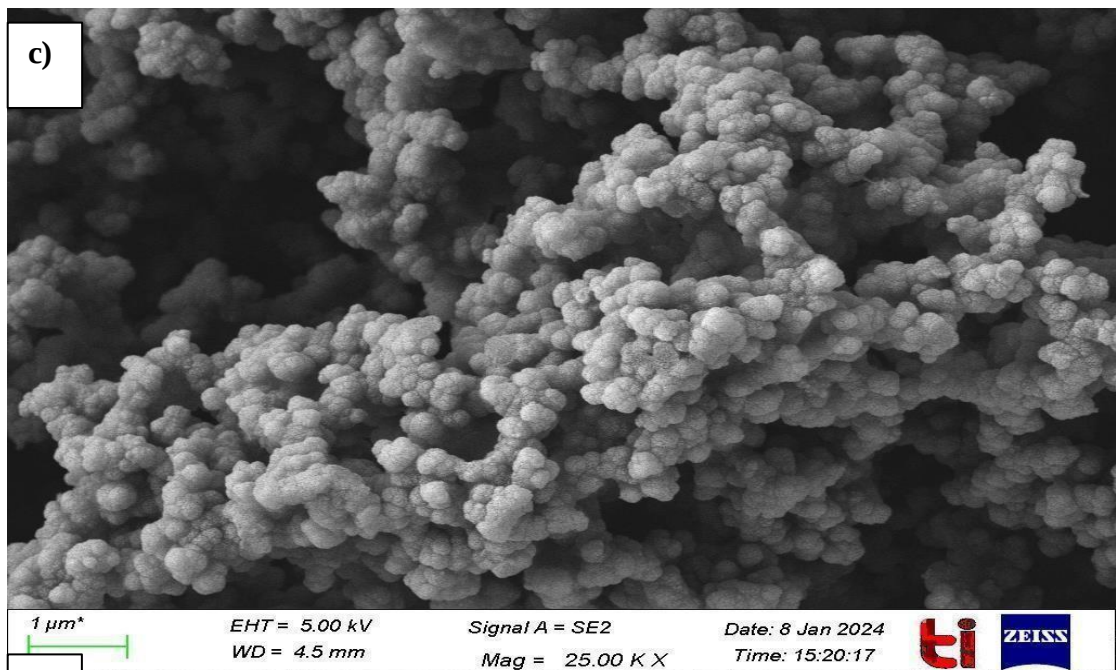
Diffraction peaks were shown at $2\theta=24.07^\circ, 25.4^\circ, 28.75^\circ, 30.6^\circ, 35.9^\circ, 43.5^\circ, 63.1^\circ$ and 71.6° corresponding to (101), (111), (004), (220), (311), (400), (511) and (620) respectively planes confirm the presence of Nickelstrontium Ferrite[133-134]. The identification of these peaks signifies the successful doping of strontium into the ferrite lattice, which plays a crucial role in enhancing the material's electrical and magnetic properties. When analyzing ferrite particles, it is observed that they exhibit lower absorption and higher diffraction due to their crystalline nature, leading to intense diffracted peaks in the XRD spectrum. However, in the case of the PPy/Ni-SrFe₂O₄ composite, the presence of a polypyrrole shell significantly reduces peak intensity. This reduction occurs because the polypyrrole shell absorbs a greater portion of the X-ray beam, resulting in diminished diffraction. This attenuation of peak intensity is a clear indication of the formation of a PPy/Ni-SrFe₂O₄ core-shell structure [135], demonstrating the successful integration of polypyrrole with the Ni-SrFe₂O₄ matrix. Fig. 2(a) shows the XRD pattern of rGO/Ni-SrFe₂O₄. It was noticed that the relative intensity of the peaks decreased due to the restacking of the rGO sheet with NSF.

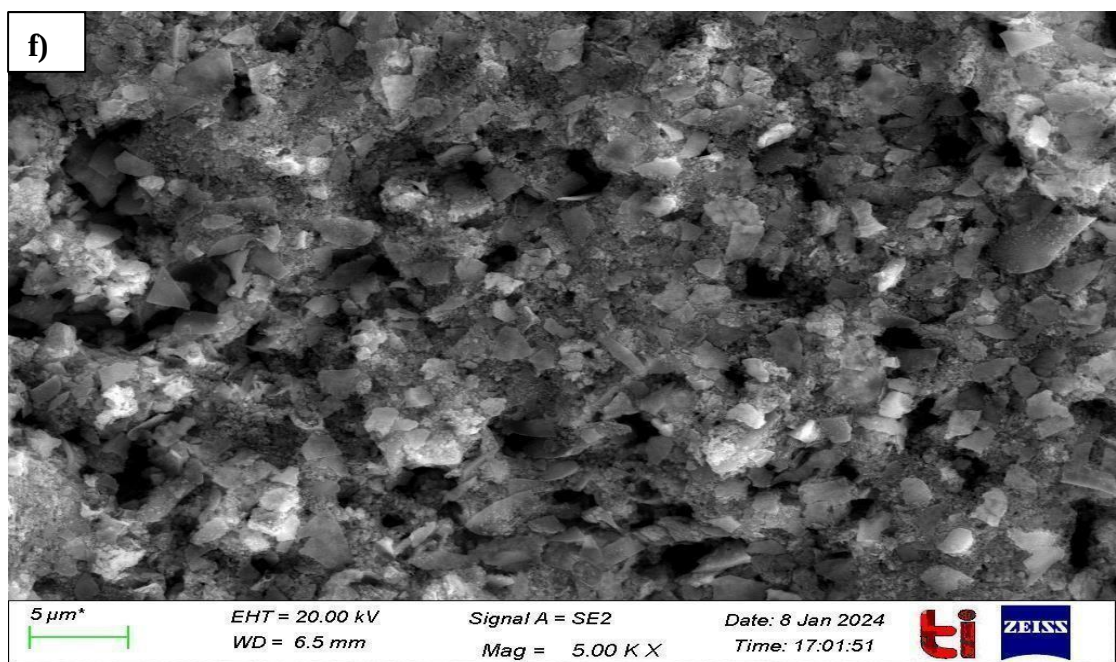
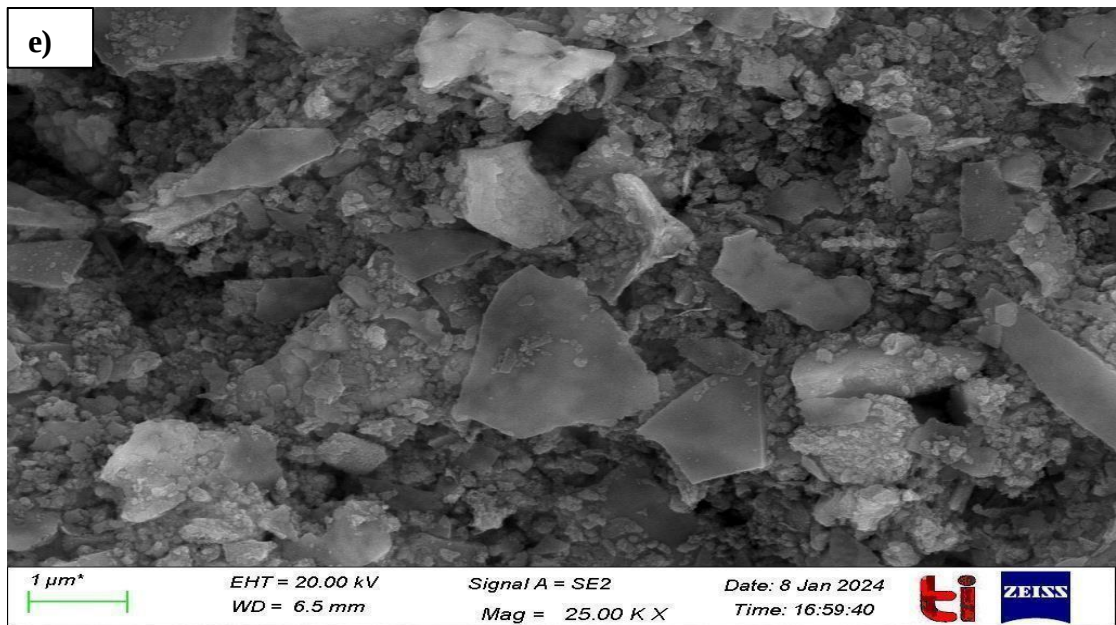
4.3 SEM analysis

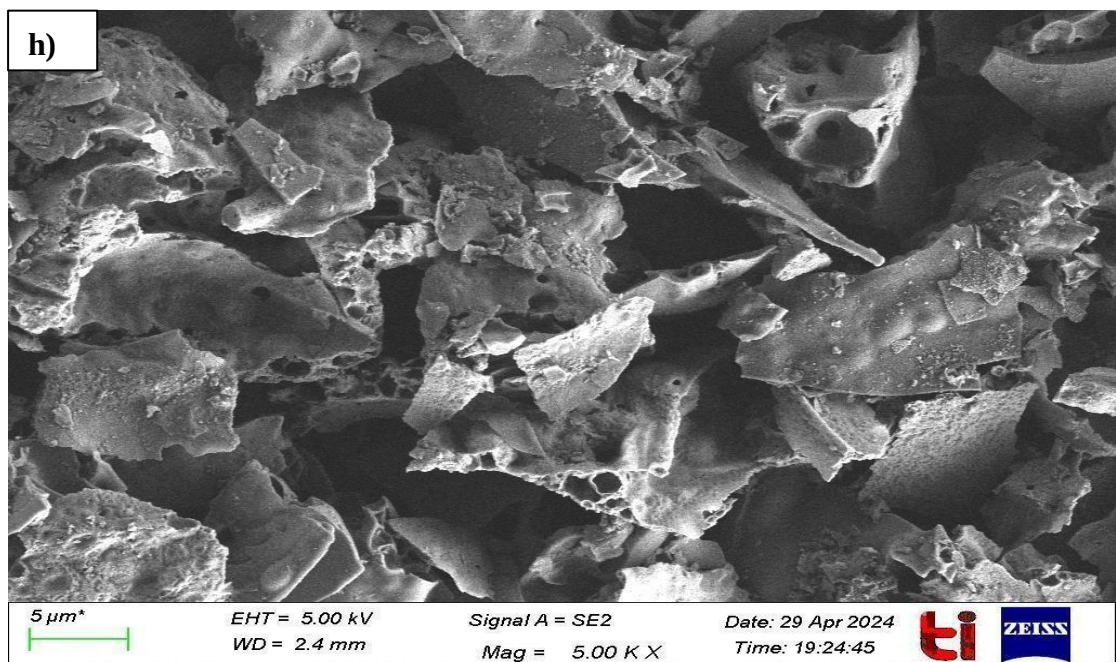
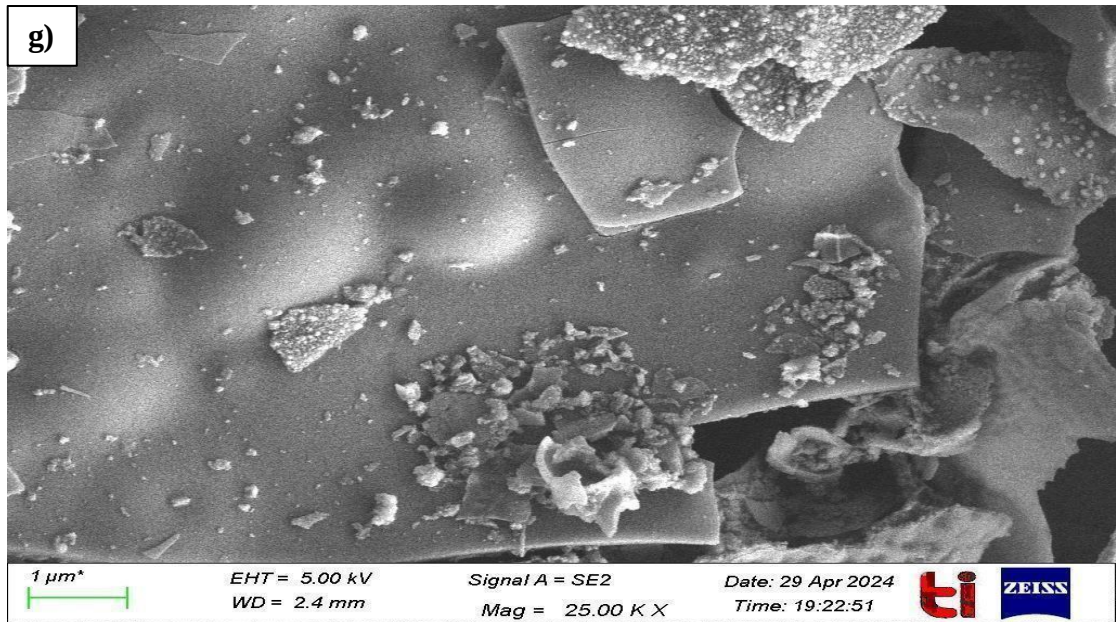
Using SEM analysis, the surface morphology of the rGO, polypyrrole, and the produced metal ferrite was examined.

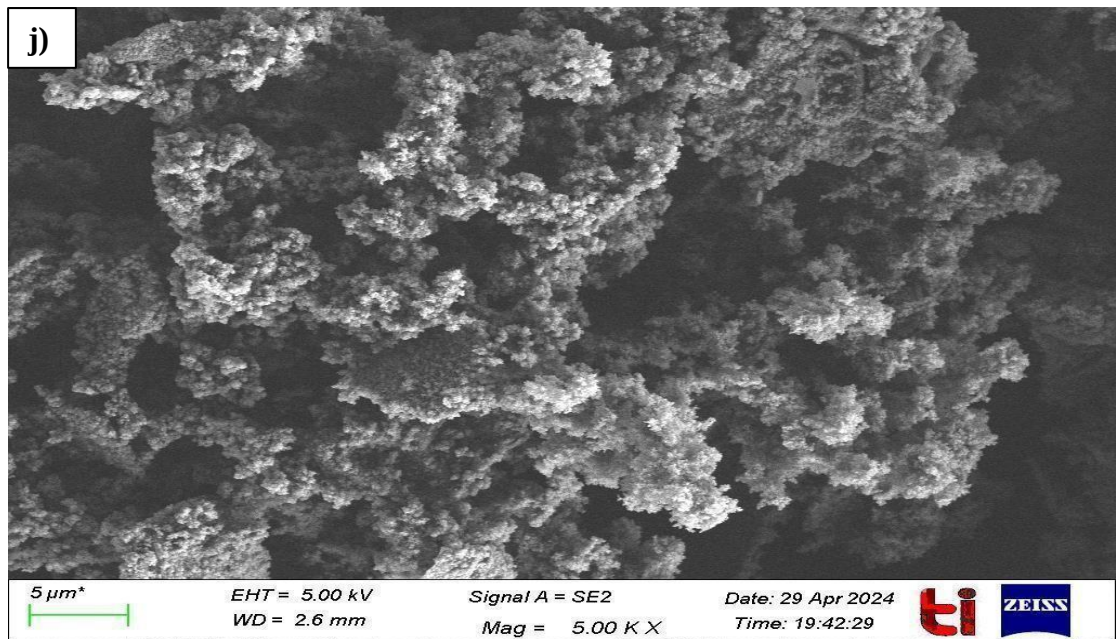
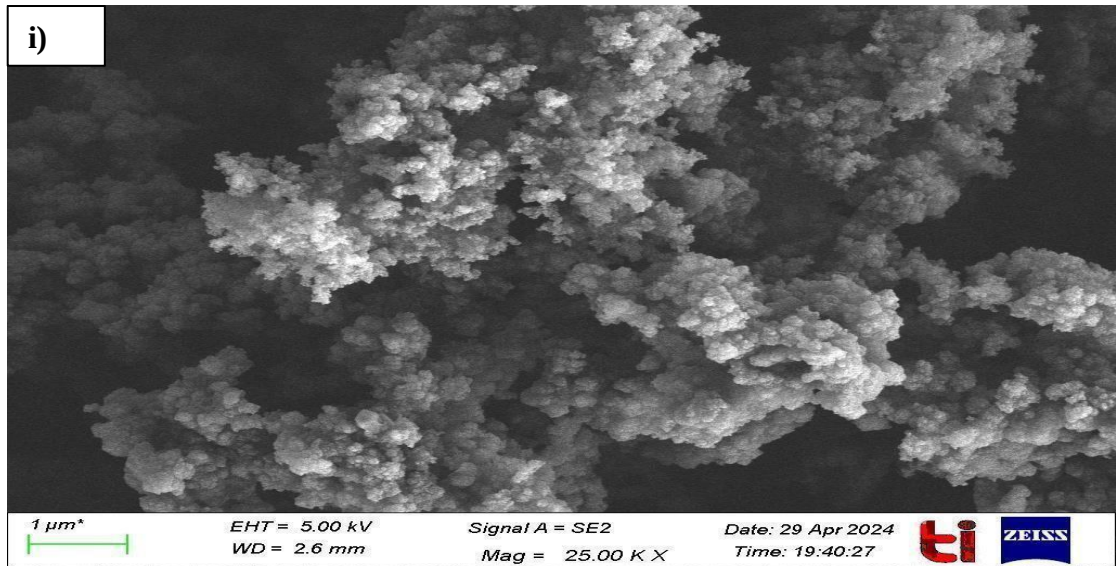
1. The porous and networked structure is beneficial for ion diffusion and charge storage in supercapacitor applications.
2. rGO sheets form a conductive network with NiSrFe₂O₄ nanoparticles, enhancing electrochemical conductivity.
3. Polypyrrole particles embedded along rGO and Ni-Sr ferrite(essentitaly preventing ppy from aggregating rather than aggregating into large granular assemblies)
4. Pores structure supports ion transport and electrolyte penetration, key for high-performance supercapacitors.











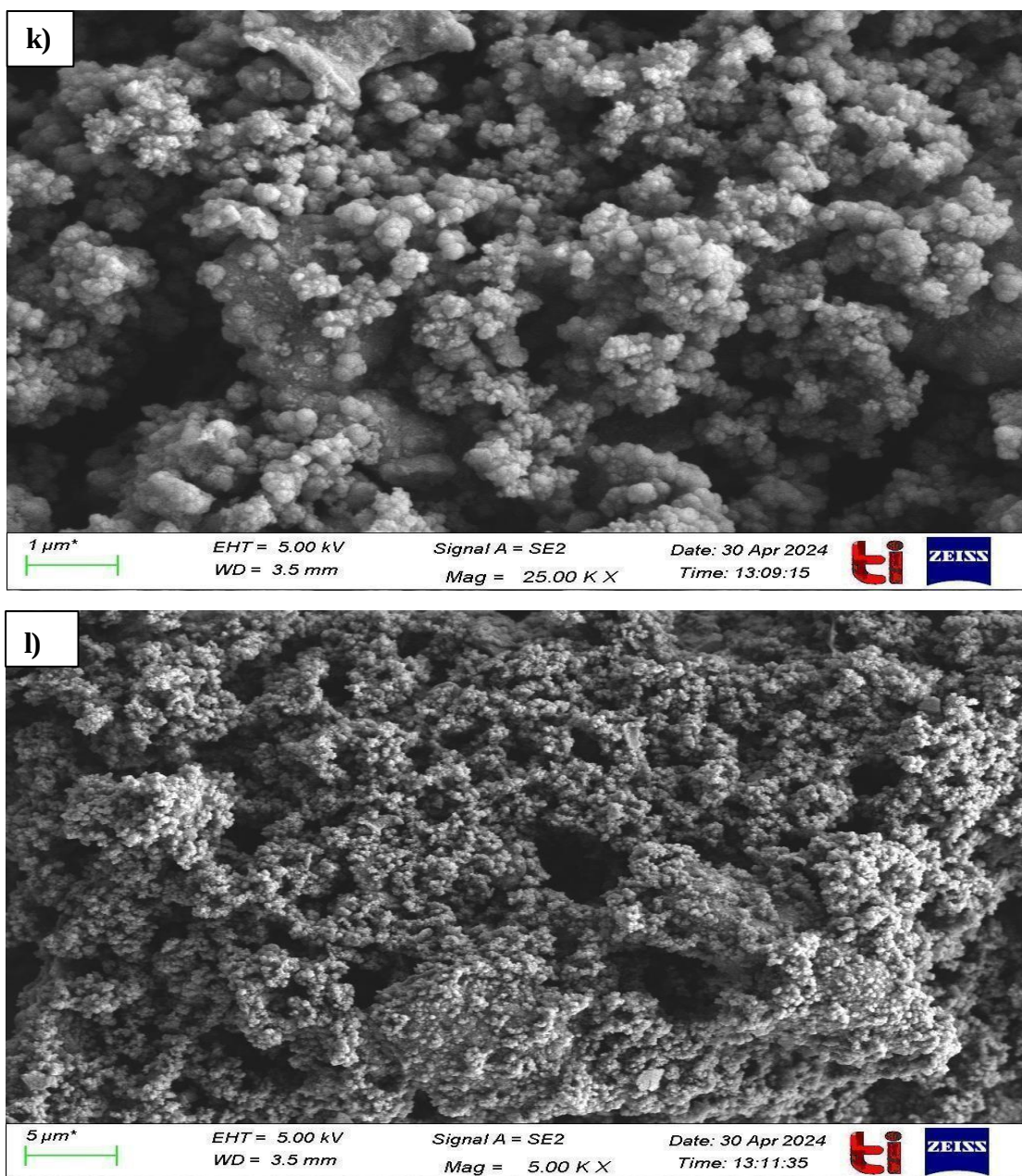


Figure 4.3.1 (a) and (b) FESEM image of rGO (c) and (d) FESEM of PPy (e) and (f) FESEM of Ni-SrFe₂O₄ (g) and (h) FESEM of rGO/Ni-SrFe₂O₄ (i) and (j) FESEM of PPy/Ni-SrFe₂O₄ (k) and (l) FESEM of PPy/rGO/Ni-SrFe₂O₄

The FESEM images of PPy reveal a unique globular morphology, characterised by a pronounced tendency to aggregate into larger clusters composed of granular structures. The observed clusters exhibit significant porosity, which facilitates the transport of electrolytes, particularly during the charging and discharging phases in electrochemical applications. The porous structure of PPy promotes effective ion transport, thereby improving its electrochemical performance. Furthermore, PPy functions as a highly efficient conducting network, greatly enhancing the electrochemical activity and the accessibility of active sites within the Ni-SrFe₂O₄ composite. The combination of PPy and Ni-SrFe₂O₄ enhances charge storage and transfer properties, essential for the functionality of supercapacitors and batteries. Even with their clustering, both Ni-SrFe₂O₄ and pure PPy nanoparticles maintain a degree of permeability, facilitating electrolyte penetration, which enhances ion diffusion and charge retention. The micrographs reveal a non-uniform distribution of grain sizes within the material, resulting in areas where specific grains aggregate to create distinct masses. The irregular distribution could impact the total surface area and the number of active sites accessible for electrochemical reactions. The elevated pore density on the PNS electrode surface enhances capacitance and accelerates charge-discharge rates. The presence of these pores increases the specific capacitance of the PNS electrode by offering more active sites for ion adsorption and desorption, thereby optimizing its energy storage capabilities. The FESEM images of PPy/rGO/Ni-SrFe₂O₄ ternary hybrids (Fig. 3) demonstrate that the integration of PPy with reduced graphene oxide (rGO)-doped metal ferrite leads to a structure characterized by high porosity. The enhanced porosity results from the collaborative interactions among the three components, facilitating the development of a well-distributed, interconnected network. The FESEM images distinctly illustrate that PPy particles uniformly cover both the rGO sheets and Ni-SrFe₂O₄ microspheres, suggesting that these surfaces served as favorable nucleation sites for the polymerization of pyrrole monomers. The consistent application of PPy across these surfaces indicates robust interfacial interactions, promoting enhanced integration of the materials at the nanoscale. Interestingly, in contrast to the pure PPy samples, which tend to form large, granular aggregates, the ternary hybrid composites exhibit PPy particles integrated along the rGO sheets and Ni-SrFe₂O₄ microspheres. This structural characteristic inhibits the over-aggregation of PPy, resulting in a more consistent distribution of polymeric particles within the composite. The effective

utilization of PPy is notably improved, leading to enhanced electrochemical performance. The integration of metal ferrite and PPy effectively prevents the restacking of graphene layers, which in turn enhances the active surface area. Preventing the reattachment of graphene layers is essential for enhancing the cyclic stability and overall electrochemical efficiency of the composite. Furthermore, both rGO and PPy serve as effective conducting networks, promoting charge transport and further improving the electrochemical properties of Ni-SrFe₂O₄. This interconnected framework enhances ion mobility and accessibility to active sites, ultimately optimizing the charge storage capabilities of the composite. Even with the clustered structure of Ni-SrFe₂O₄ and rGO nanoparticles, they maintain permeability, facilitating effective electrolyte infiltration and charge transfer. The composite ferrite demonstrates low densification and a highly porous microstructure, positioning it as a promising option for energy storage applications, including supercapacitors and advanced battery technologies. With evenly distributed Ni-SrFe₂O₄ nanoparticles implanted in the rGO and PPy matrix, the sponge-like porosity structure is a distinctive characteristic of all the composites in the PRNS series. The addition of PPy is essential for improving the composites' structural integrity and electrical conductivity. In order to maximize electrochemical performance, the rGO framework facilitates the dispersion of the Ni-SrFe₂O₄ particles and guarantees efficient contact with electrolytes[70,136]. The PPy/rGO/Ni-SrFe₂O₄ composites were successfully synthesized, as confirmed by the FESEM analysis, which also highlights the well-defined porosity architectures, uniform nanoparticle distribution, and efficient PPy incorporation. With its porosity and homogeneous dispersion of nanoparticles, this ordered structure enhances the composites' electrochemical performance and qualifies them as candidates for cutting-edge energy storage applications.

4.4 FTIR Analysis

Fourier Transform Infrared (FTIR) spectroscopy is a crucial analytical technique for characterizing nanocomposites, as it helps identify the presence of specific functional groups such as hydroxyl, carbonyl, and metal-oxygen bonds. These functional groups play a vital role in determining the interactions between different constituents within the composite material. Understanding these interactions is essential for optimizing the structural, chemical, and electrochemical properties of nanocomposites, particularly in energy storage applications. FTIR is especially valuable for assessing the chemical

environment and bonding structure of active materials in energy storage devices. The nature and distribution of functional groups directly influence the electrochemical activity, conductivity, and stability of the materials, impacting overall device performance. For this study, FTIR spectroscopy was conducted in the 400-4000 cm^{-1} region to confirm phase formation and accurately identify functional groups. This analysis provided critical insights into the successful integration of various materials and their suitability for energy storage applications.

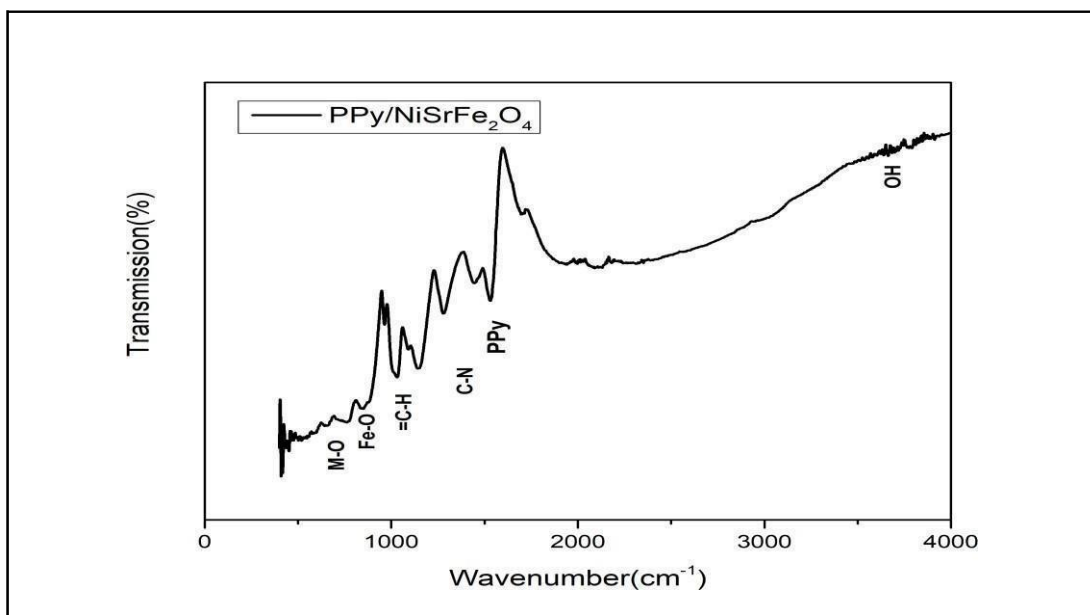


Fig.4.4.1 FTIR spectrum of binary composite PPy/Ni-SrFe₂O₄

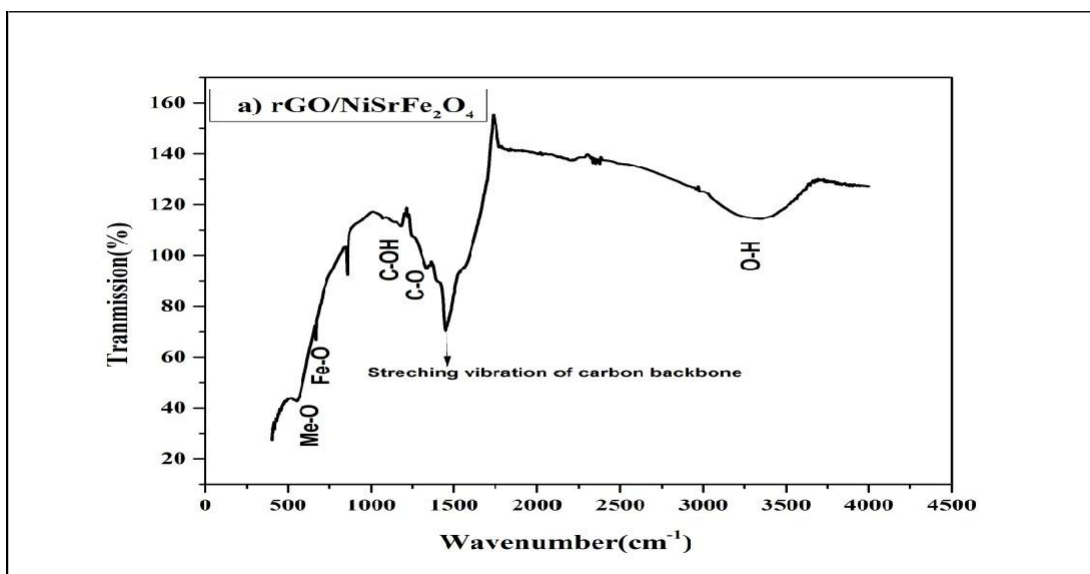


Fig. 4.4.2 FTIR spectrum of binary composite rGO/Ni-SrFe₂O₄

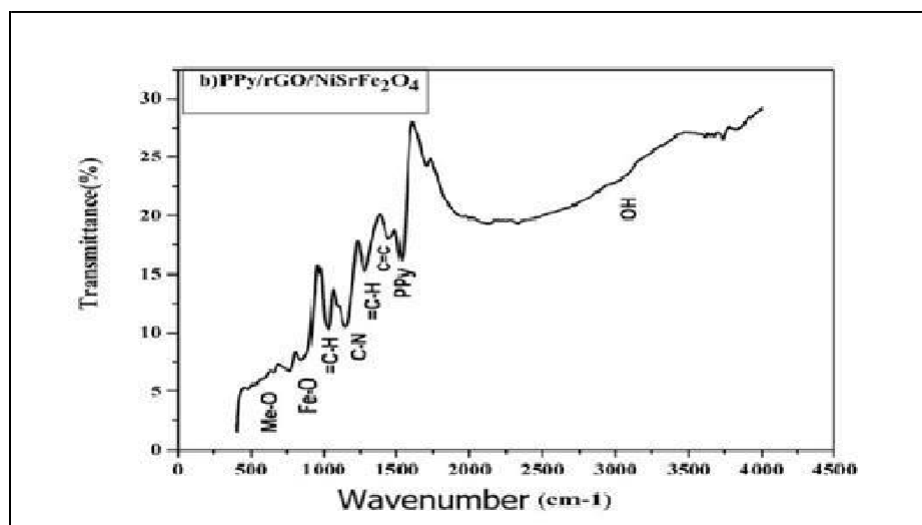


Fig.4.4.3 FTIR spectrum of ternary composite PPy/rGO/Ni-SrFe₂O₄

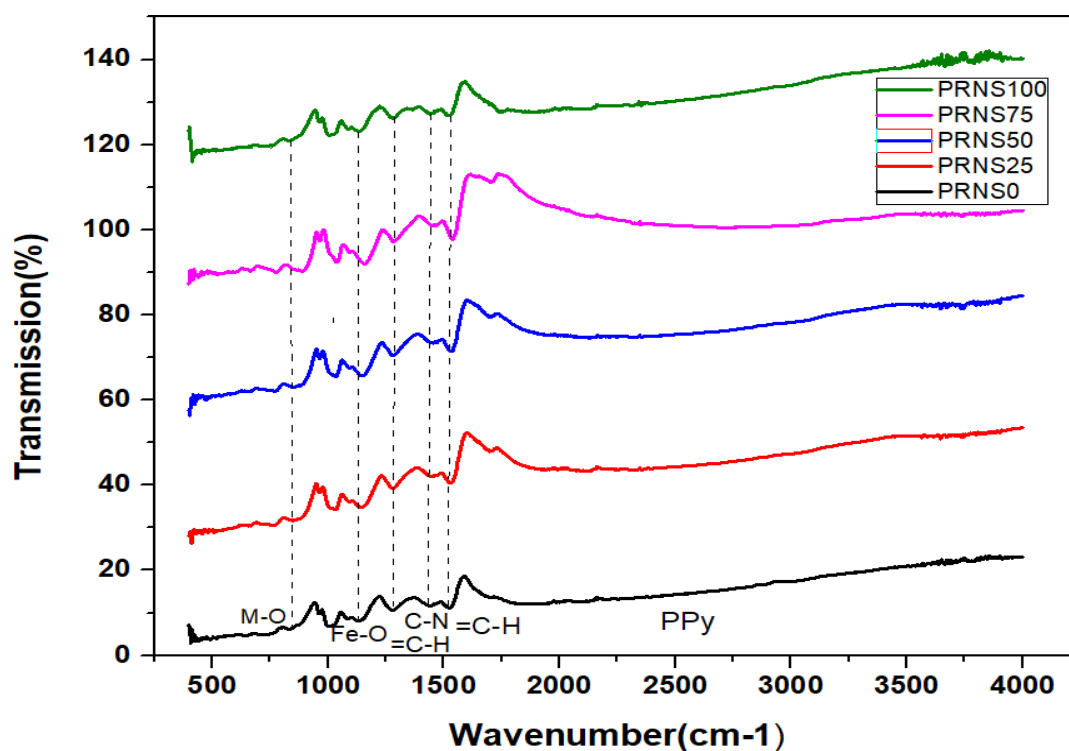


Fig.4.4.4 FTIR spectrum of ternary composite PPy/rGO/Ni-SrFe₂O₄(with Varying ratio of Ni and Sr)

The characteristic absorption bands of polypyrrole (PPy) were observed at 763 cm^{-1} , 963 cm^{-1} , 1031 cm^{-1} , 1091 cm^{-1} , 1142 cm^{-1} , 1278 cm^{-1} , 1444 cm^{-1} , 1531 cm^{-1} , and 3791 cm^{-1} , confirming the presence of its distinct functional groups. The prominent peaks at 1552 cm^{-1} and 1464 cm^{-1} correspond to C=C stretching vibrations, indicative of the conjugated structure of PPy. The peak at 1314 cm^{-1} represents C-N bonding, which is characteristic of polypyrrole's polymer backbone[137,138]. For reduced graphene oxide (rGO), the presence of aromatic C=C bonds is confirmed by the absorption peak at 1604 cm^{-1} , which signifies the hybrid sp^2 structure of graphene sheets. The peak detected at 1420 cm^{-1} represents the presence of carboxyl (C-O) functional groups, further validating the oxidation and reduction processes in rGO. Additionally, N-H and C-H stretching vibrations were observed at 3439 cm^{-1} and 2929 cm^{-1} , respectively, signifying the presence of polypyrrole. The Ni ferrite peaks appeared at 554 cm^{-1} , 1031 cm^{-1} , 1531 cm^{-1} , and 3791 cm^{-1} [138], while Sr ferrite exhibited absorption bands at 441 cm^{-1} , 546 cm^{-1} , 596 cm^{-1} , and 1458 cm^{-1} . Furthermore, the peak at 1444 cm^{-1} is attributed to the stretching of C=C bonds and is influenced by the stretching vibrations of Fe-O and Sr-O bonds [139,140]]. These metal-oxygen bonds and functional groups are essential for improving the composites' structural stability and electrochemical performance. In particular, the conductive qualities of polypyrrole enhance charge transport and pseudo capacitance, while the metal-oxygen linkages support redox activity. Furthermore, the conductive matrix offered by the rGO framework facilitates ion transport and improves the composite's overall performance in energy storage devices. The structural complexity and adaptability of the PRNS composites are demonstrated by the combination of metal-oxygen vibrational modes with polymer and hydroxyl group modes. Each component of the composite has a unique role in boosting its electrochemical capabilities, and this interaction of rGO, PPy, and Ni-SrFe₂O₄ adds to the synergistic effects seen in the composite. These spectral characteristics confirm the successful integration of Ni-Sr ferrite, rGO, and polypyrrole, ensuring their structural and functional compatibility.

4.5 Electrochemical analysis

Electrochemical analysis is a strong way to study the electrochemical properties of materials, especially when it comes to storing and converting energy. This gives you a basic understanding of how charge storage works, how conductive it is, how it reacts

with other chemicals, and how stable it is overall in an electrochemical sense. This study is very important for figuring out how well the materials used in supercapacitors, batteries, and fuel cells work. CV, GCD, and EIS are all important electrochemical methods. The CV method lets you look at redox reactions and how charge is stored, while the GCD method gives you information about specific capacitance and energy efficiency. EIS also looks at ion diffusion and charge transfer resistance. These methods help improve electrode materials by testing their conductivity, stability, and ability to store energy. The electrolyte used in the electrode system was a 3M KOH solution. The working electrode was made of nickel foam that had been coated with a slurry of active material. The chosen electrolyte has a wide electrochemical window and a high ionic conductivity. We tested the electrochemical performance of the samples we made using three-electrode systems and a 3M aqueous KOH electrolyte. The CV curve also shows that the stable concentration of cations and anions on the surface of the electrode is very reversible. The anodic and cathodic peaks in the CV curve are caused by the oxidation and reduction of Sr and Ni ions. These peaks are linked to the adsorption and desorption of surface (OH⁻) ions, respectively.

Fig.4.5.1 Synthesis and characterization of composites

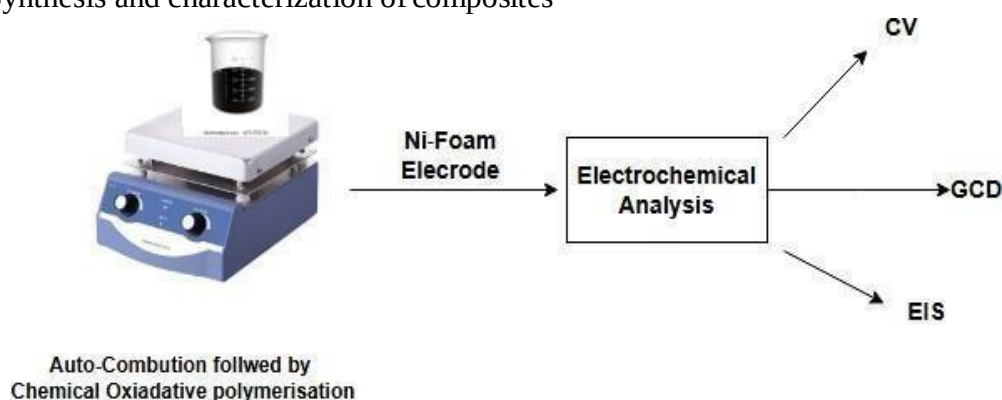




Fig.4.5.2 Electrochemical set-up

4.5.1 Cyclic Voltammetry (CV)

Cyclic voltammetry (CV) is a common electrochemical method for studying the redox behavior, charge storage capacity, and stability of electrode materials. It is a dynamic method that measures the current response of a system as the applied voltage is cycled between two set limits. This method gives us important information about the electrochemical processes that happen at the interface between the electrode and the electrolyte. It is necessary for studying supercapacitors, batteries, fuel cells, and biosensors. During CV, the potential is swept at a set scan rate, and the current that comes out is recorded to make a voltammogram. This helps figure out redox peaks, capacitance, reaction kinetics, and charge transfer mechanisms. The voltammogram's shape and area give important information about how reversible redox reactions are, how diffusion works, and how much capacitance electrode materials have. Cyclic voltammetry is a basic tool in electrochemical analysis that helps improve materials for energy storage by testing their electrochemical stability, conductivity, and performance under different conditions CV was used to assess the (PPy/Ni-SrFe₂O₄) composite's electrochemical performance. Figures below displays CV curves of PNS for different scan rates. PPy/Ni-SrFe₂O₄ nanocomposite exhibits

oxidation-reduction peaks. The PNS electrode's pseudocapacitive behavior is caused by these redox peaks. The specific capacitance was calculated using equation (1)

$$C_m = \frac{dQ}{mdV} = \frac{idt}{mdV} = \frac{1}{2mv(V_1-V_2)} \int_{V_1}^{V_2} i(V)dV \quad -(1)$$

$$S = \int_{V_1}^{V_2} i(V)dV$$

Where dV stands for scanning rate (Vs^{-1}), m (g) is the mass of active material, S (cm^2) is the area of a CV curve in a single circle, and V1 and V2 signify the lower and upper limit potentials (V), respectively. according to the CV graphs of binary (RNS) and ternary (PRNS) composites at various scan rates. The faradaic contribution of the redox processes in PPy is the source of the capacitive behavior of PPy and its hybrids [3]. Due to the double-layer contribution from rGO, binary hybrid RNS displayed a significantly larger rectangle-like area, even though metal ferrite has several oxidation states and may display similar features. PRNS ternary hybrids have larger CV graph regions than binary RNS hybrids.

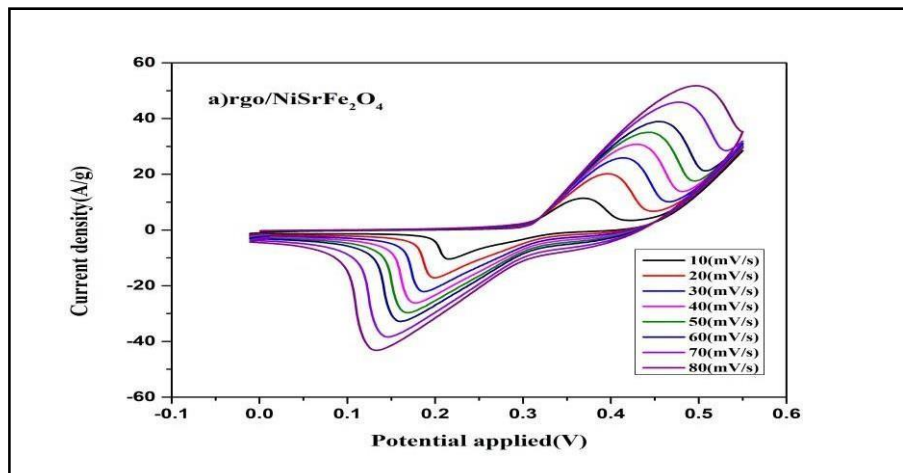


Fig.4.5.3 CV curves binary composite rGO/NiSrFe₂O₄

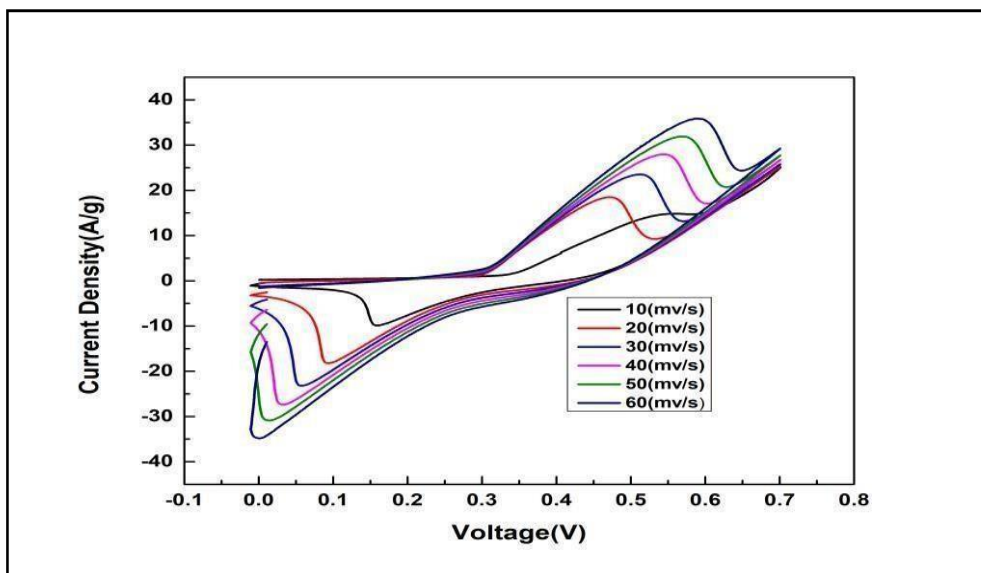


Fig.4.5.4 CV curves binary composite PPy/NiSrFe₂O₄

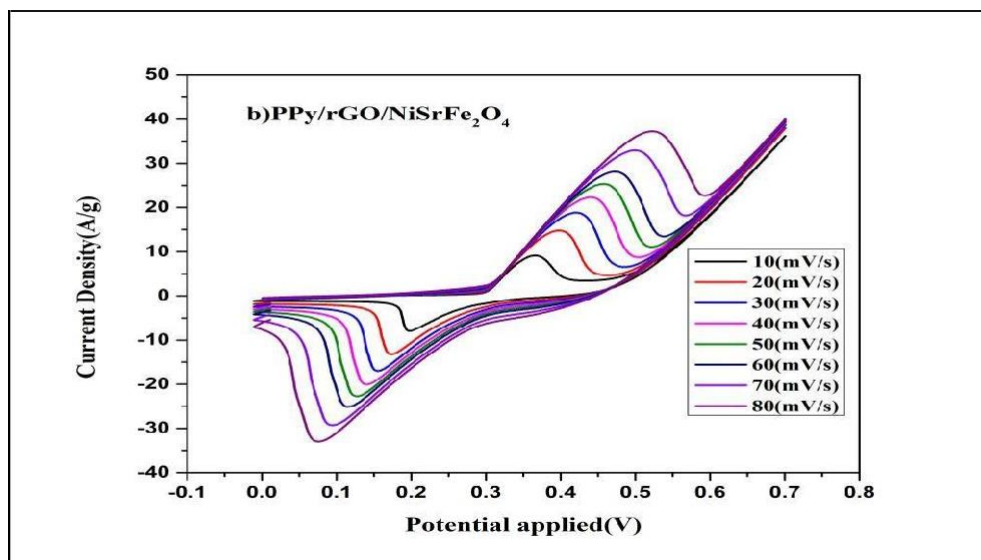
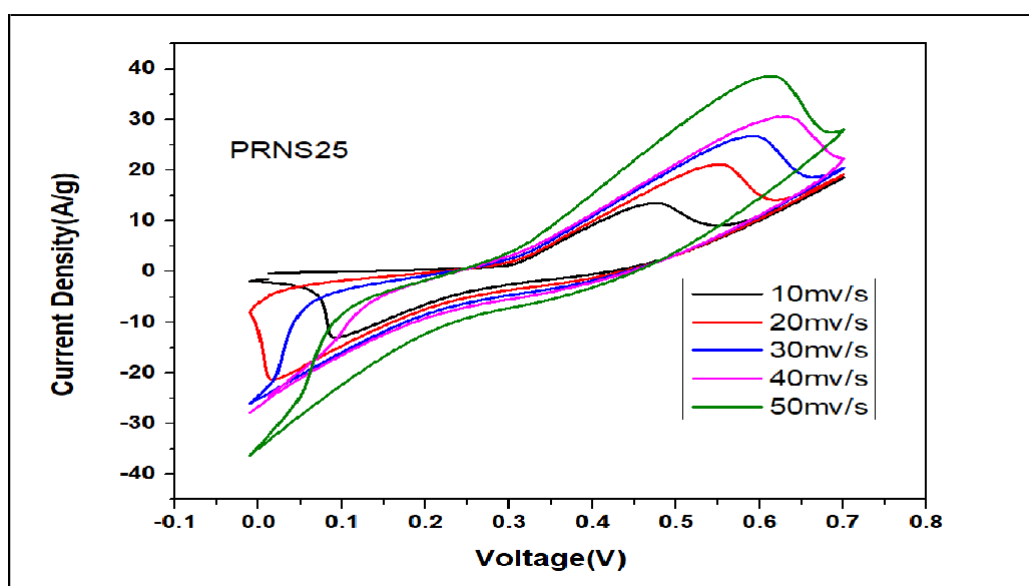
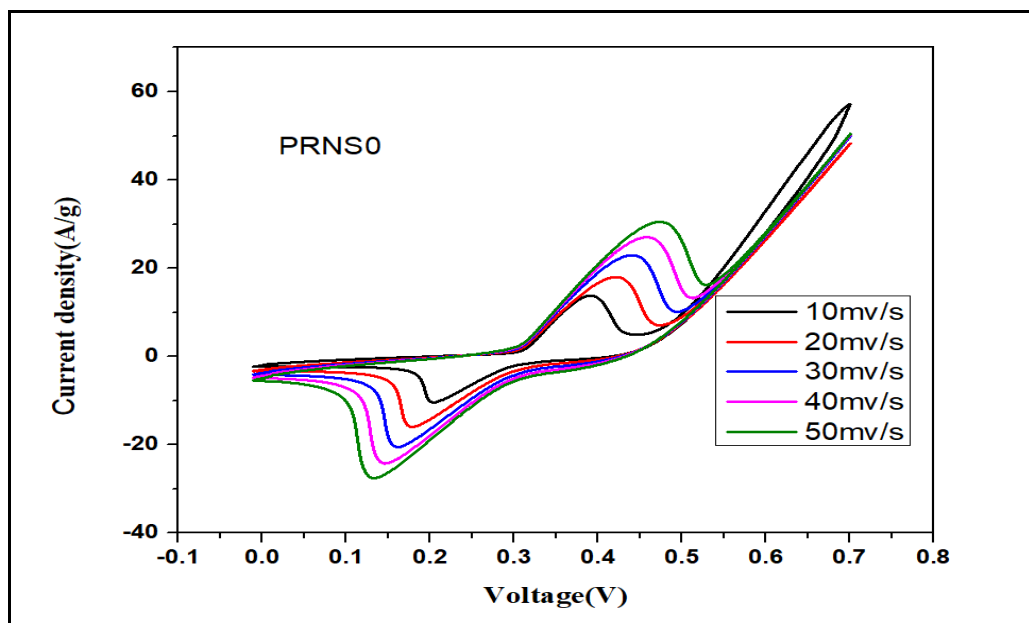


Fig.4.5.5 CV curves ternary composite PPy/rGO/Ni-SrFe₂O₄



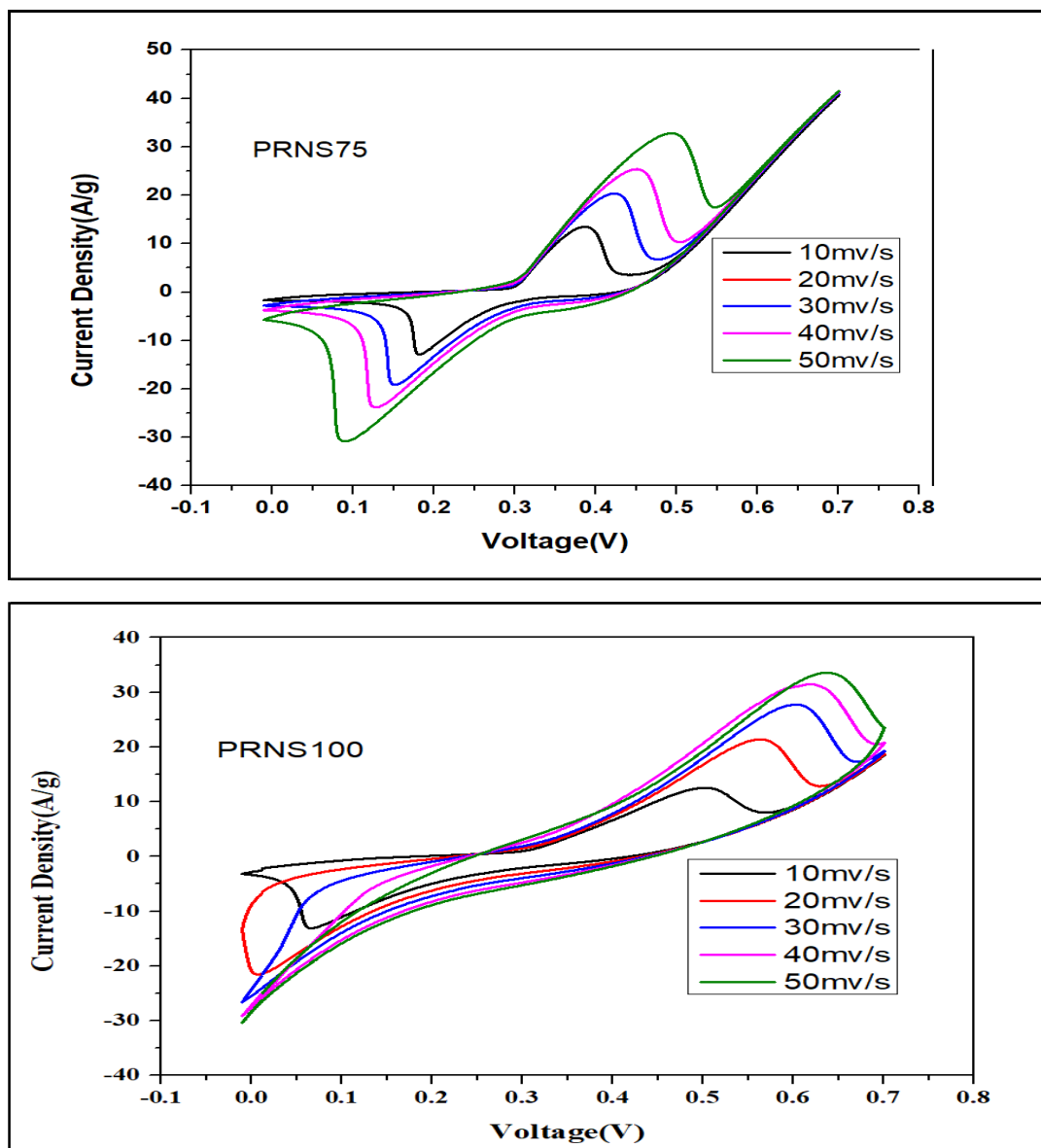


Fig 4.5.6 CV curves of PPy/rGO/Ni-SrFe₂O₄ with varying ratio of Ni and Sr

The pseudo-capacitive behavior resulting from the reversible electrochemical process influences the capacitance of Ni-SrFe₂O₄, as it functions as a pseudocapacitive electrode. This is evidenced by the presence of a reversible redox peak, which signifies the electron exchange associated with charge transfer and the faradaic charge storage mechanism. The analysis of cyclic voltammetry indicates that as the scan rate for the NF electrode increases, both anodic and cathodic current peaks consistently rise. Higher scan rates result in an elevated current density; however, they concurrently cause a reduction in capacitance, as the rapid rates limit the electrode's ability to exchange

electrons with the electrolyte effectively[133,141]. The specific capacitance exceeds that observed when rGO is absent from the electrode structure, as the placement of NiFe_2O_4 on the rGO surface enhances electrical conductivity and creates robust conducting pathways for charge transfer. The specific capacitance observed between NiFe_2O_4 nanoparticles and KOH electrolytes constitutes a significant portion of the total capacitive characteristics. In comparison to pure NiFe_2O_4 nanoparticles and the rGO/ NiFe_2O_4 nanocomposite, the specific capacity of rGO is notably low, and it exhibits the electrochemical double-layer capacitor mechanism for charge storage. Additionally, the charge-discharge curves exhibit nonlinearity, reinforcing the findings from the CV analysis and highlighting the significance of the faradaic redox reaction [134]. Furthermore, the capacitance values for the identical material in GCD and CV exhibit discrepancies. The capacitance value in GCD is lower than in CV due to the current density hindering surface ion access and the less effective faradic mechanism, while in CV, the capacitance value is based on the entire surface area.

Table 4.5.1: Specific capacitance values for binary and ternary electrodes at various scan rates

Scan rate mV/s	10	20	30	40	50	60
Specific capacitance(F/g) of rGO/Ni-Sr ferrite	516	351	287	252	229	198
Specific capacitance(F/g) of PPy/Ni-SrFe ₂ O ₄	654	415	333	289	260	244
Specific capacitance(F/g) of PPy/rGO/Ni-SrFe ₂ O ₄	710	421	316	261	227	201

Table 4.5.2 Specific capacitance values of PPy/rGO/Ni-SrFe₂O₄ with varying ratio of Ni and Sr

Scan rate(mV/s)	10	20	30	40	50
Specific capacitance(F/g)	C _{sp0}	C _{sp25}	C _{sp50}	C _{sp75}	C _{sp100}
PRNS ₀	113	565	425	347	298
PRNS ₂₅	612	433	365	317	322
PRNS ₇₅	900	538	407	337	293
PRNS ₁₀₀	569	402	335	299	250

Using CV with varying weight % of Ni and Sr from (0%-100%) doped with PPy/rGO/Fe₂O₄, experimental results showed the specific capacitance for PRNS₀, PRNS₂₅, PRNS₅₀, PRNS₇₅, and PRNS₁₀₀. Due to its exceptional electrochemical

characteristics, the hybrid material that was created is a very attractive option for a number of energy storage uses. The ternary composites' notable capacitance improvement demonstrates the complementary effects of PPy, rGO, and NiSrFe₂O₄, suggesting that this technique has the potential to produce high-performance supercapacitor electrodes.

The composite's maximum specific capacitance was 900F/g for a combination of PRNS₇₅ at a scan rate of 10mV/s. The ideal composition, in which the nickel content improves both conductivity and charge storage capacity, is principally responsible for this higher performance. Because of its porous structure, the PPy component makes it easier for electrolyte penetration and charge storage. Additionally, the PPy network facilitates quick electron and ion content, which, when combined with the complementary actions of rGO, NiSrFeO₄, and PPy, leads to increased redox activity and conductivity. The homogeneity of the composite is greatly enhanced by the presence of PPy, which also improves charge transport capacities and permits effective electrolyte access. More charge storage and more distinct CV peaks result from the improved redox and conductivities caused by the higher nickel content. However, because of less efficient ion diffusion and charge transport within the structure, the overall electrochemical performance is still inferior to that of the composites with a larger nickel concentration. The redox potential of Ni-SrFe₂O₄ and the conductive qualities of rGO are primarily responsible for the steady redox activity shown in the CV profiles for the PRNS series. The specific capacitance of the PRNS₇₅ composite was 900 F/g. The specific capacitance is larger than PRNS₂₅, PRNS₅₀, PRNS₇₅ and PRNS₁₀₀, which are displayed in Table 4.5.2. This is probably because the FESEM pictures show a denser structure and greater particle size, which limit electrolyte access and ion transport. However, PRNS's consistent response at different scan speeds attests to its dependable electrochemical performance. Every compound in the PRNS family has a consistent CV profile, with distinct redox peaks signifying efficient charge storage and recovery. The performance of the composites demonstrates the synergistic relationship between rGO, Ni-SrFe₂O₄, and PPy, as their combination improves conductivity, redox activity, and overall charge transport capacities. The well-balanced composition of the best-performing composites, PRNS₇₅, maximizes the materials' redox characteristics and conductivity. The overall findings of the cyclic voltammetry demonstrate the strong electrochemical performance

of (PPy/rGO/Ni-SrFe₂O₄) composites, which make them appropriate for electrochemical energy storage applications and potentially even useful in super capacitors and other related devices. It is possible to conduct additional research and optimization for certain energy storage system applications. The composite's maximum specific capacitance was 900F/g for a combination of PRNS₇₅ at a scan rate of 10mV/s. The overall findings of the cyclic voltammetry demonstrate the strong electrochemical performance of (PPy/rGO/Ni-SrFerrite) composites, which make them appropriate for electrochemical energy storage applications and potentially even useful in super capacitors and other related devices.

4.5.2 Galvanostatic charge-discharge (GCD)

Galvanostatic charge-discharge (GCD) is an important electrochemical method for testing how much energy electrode materials can store, how well they work, and how stable they are when they are cycled. This method involves applying a steady current to an electrode and keeping an eye on how the voltage changes over time. People often use this to test supercapacitors, batteries, and other electrochemical energy storage systems. The GCD method gives important information about an electrode's specific capacitance, energy density, power density, and charge-discharge efficiency. The shape of the charge-discharge curve is very helpful for figuring out the main way the charge is stored. It can show whether the charge storage is based on electrostatic double-layer capacitance (EDLC) or pseudocapacitive redox reactions. The straightness of the discharge curve shows that the processes of ion diffusion and charge transfer are steady. By looking at GCD curves, we can determine the stability, efficiency, and long-term performance of energy storage materials. This makes it an important tool for designing high-performance supercapacitors and advanced battery systems. The figures below shows the charging and discharging curves for RNS binary and PRNS ternary hybrids. These curves show the results of GCD measurements taken at current densities of 1 A/g, 2 A/g, 4 A/g, and 6 A/g. The findings indicate that with an increase in current density across all samples, there is a corresponding decrease in discharge duration, suggesting that the charge-discharge process is influenced by kinetic factors. This behavior is characteristic of supercapacitors, where increased current densities lead to quicker depletion of stored charge, thereby shortening the overall discharge time.

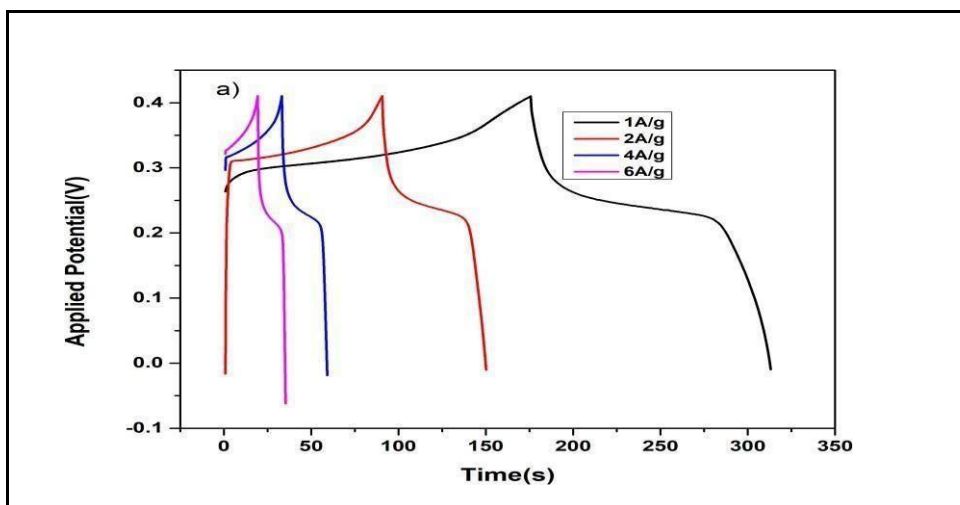


Fig.4.5.7 GCD curves for binary composite PPY/NiSrFe₂O₄

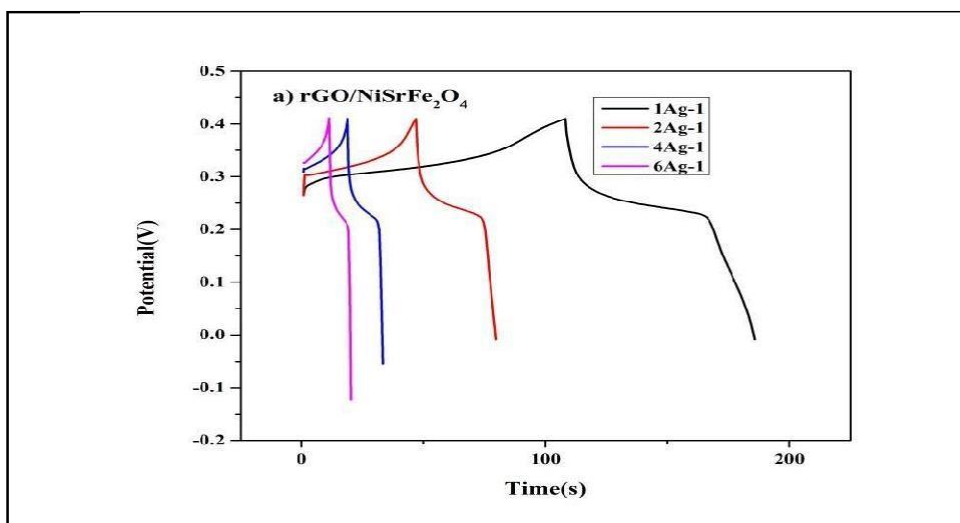
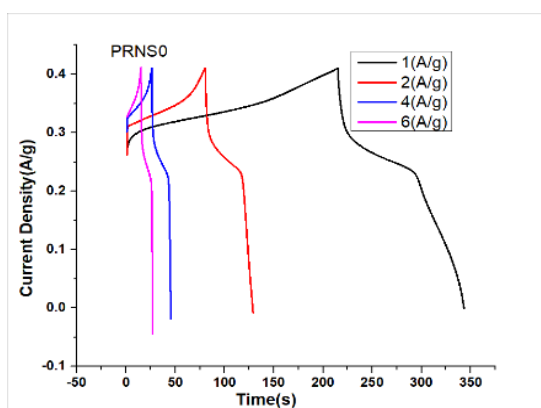
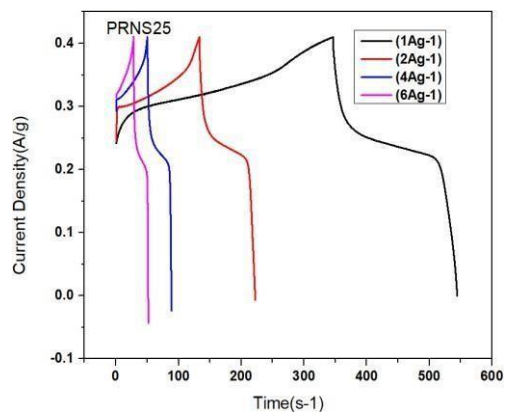


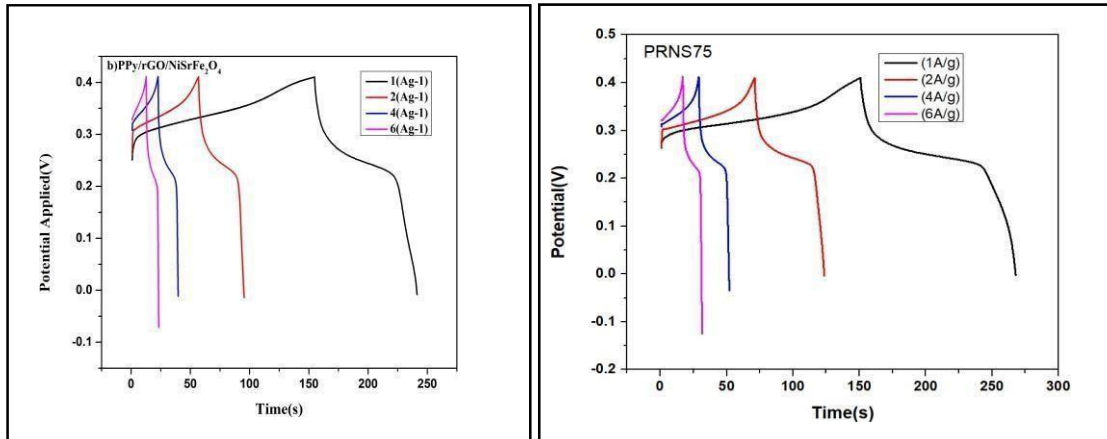
Fig.4.5.8 GCD curves for binary composite rGO/NiSrFe₂O₄



(a) GCD of PRNS₀

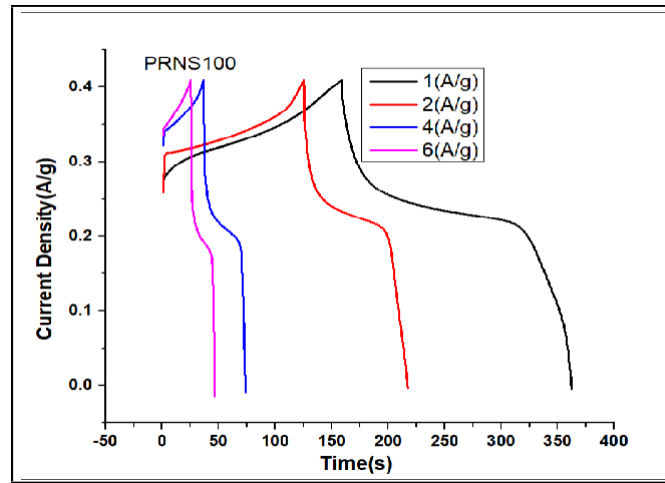


(b) PRNS₂₅



(c)PRNS₅₀

(d)PRNS₇₅



(e)PRNS₁₀₀

Fig.4.5.9GCD curves for ternary PPy/rGO/Ni-SrFe₂O₄

To evaluate the charge storage performance of the electrode materials, the specific capacitance was calculated using Equation (2):

$$C_p = (Im \times \Delta t) / \Delta V \quad (2)$$

Where (V) is the potential window, I (A) is the discharge current, Δt (s) is the discharge duration, and m (g) is the mass in grams of the active material.

where C_m represents the specific capacitance (F/g), I (A) is the discharge current, Δt (s) is the discharge duration, m (g) is the mass of the active material, and V (V) is the

applied potential window. This equation provides a quantitative measure of the electrode's ability to store and deliver charge efficiently. The non-linear shape of the GCD curves confirms the pseudocapacitive nature of the electrode materials, as seen within the voltage range of approximately 0-0.4 V in 3M KOH electrolyte. This non-linearity, particularly the presence of plateaus in the discharge curves, is indicative of the faradaic redox reactions occurring within the composite material. The results show that the binary composite. The discharge time serves as a vital metric in evaluating the performance of these electrodes, with extended discharge periods reflecting greater material capacity and improved electrochemical properties. The behavior of the electrodes concerning GCD was examined in a 3M KOH electrolyte across a voltage range of roughly 0–0.4V. The non-linear characteristics of the GCD curves, illustrated in Fig.4.5.7 to 4.5.9. validate the pseudocapacitive behavior of the electrode material, which can be linked to the faradaic redox reactions taking place within the composite structure. The binary composite rGO/Ni-SrFe₂O₄ exhibited a specific capacitance of 207F/g at a current density of 1 A/g indicating its moderate charge storage capabilities. For current densities at 1Ag⁻¹, the specific capacitance of PPy/Ni-SrFe₂O₄ is 342F/g, The composite's stability and high-rate performance were proved by its ideal capacitance behavior during charge and discharge. These results demonstrate the promise of PPy/NiSrFe₂O₄ for advanced energy storage applications due to its high specific capacitance, long discharge durations, and reliable electrochemical performance. Upon the incorporation of polypyrrole, the ternary composite PPy/rGO/Ni-SrFe₂O₄ demonstrated a notable improvement in electrochemical performance, achieving a high specific capacitance of 517 F/g at 1 A/g The observed rise in specific capacitance can be linked to the synergistic influence of PPy, which improves electrical conductivity and adds to the pseudocapacitive characteristics, resulting in enhanced charge storage efficiency. Furthermore, the discharge duration of the ternary composite was significantly extended in comparison to the binary composite, suggesting an enhanced energy storage capacity. The extended discharge duration indicates that incorporating PPy enhances charge retention and contributes to a more stable electrochemical environment, which is crucial for applications in long-term energy storage. The excellent capacitive performance of both composites throughout charge and discharge

cycles further validates their stability and high-rate capability. The reduction in capacitance as current density rises is a typical occurrence in supercapacitor materials, linked to the restricted diffusion of electrolyte ions at elevated charge-discharge rates. The retention of a substantial portion of the initial capacitance, even under high current densities, indicates that the composite exhibits remarkable rate capability and minimal internal resistance. The discharge time of the ternary composite underscores its remarkable energy storage potential. The prolonged duration of the discharge phase indicates that the electrode material is capable of maintaining extended charge storage, which is essential for effective energy storage applications. The almost triangular configuration of the GCD curves signifies effective charge storage and release, showcasing the electrode's swift charge-discharge response and minimal internal resistance. Moreover, the uniformity of the charge-discharge curves at varying current densities highlights the stability and dependability of the PPy/Ni-SrFe₂O₄ electrode material. The consistency observed in GCD profiles indicates negligible degradation throughout repeated cycling, underscoring the enduring electrochemical stability of the composite. The addition of rGO inhibits the reattachment of graphene layers, which enhances the active surface area and promotes improved ion diffusion. The networks established by PPy and rGO work together to boost electrochemical activity and create more active sites for redox reactions, thereby enhancing charge storage capacity[97,142].

Table 4.5.3 The specific capacitance values using GCD curves

Current density (A/g)	1	2	4	6
Specific capacitance F/g of (rGO/Ni-Sr ferrite)	207	205	155	150

Ppy/Ni-SrFe ₂ O ₄	342	295	260	240
Ppy/rGO/Ni-Sr ferrite	517	491	422	394

Table 4.5.4 The specific capacitance values using GCD curves of PRNS with varying ratio of Ni and Sr

Scan rate(Ag-1)	1	2	4	6
Specific Capacitance	C _{SP1} (F/g)	C _{SP2} (F/g)	C _{SP4} (F/g)	C _{SP6} (F/g)
PRNS ₀	196	176	151	127
PRNS ₂₅	326	266	223	197
PRNS ₅₀	517	491	422	394
PRNS ₇₅	675	606	493	400
PRNS ₁₀₀	388	346	293	280

In summary, the GCD analysis provides compelling evidence for the efficacy of the PPy/rGO/Ni-SrFe₂O₄ electrode as a superior supercapacitor material. Every GCD curve at every current level has nearly the same form, indicating the electrode material's outstanding capacitive performance. The F/g ratio represents the specific capacitance. For 1A/g, 2A/g, 4A/g and 6A/g current densities. The electrochemical performance of the PPy/rGO/Ni-SrFe₂O₄ composites is crucially shown by the GCD curves. The

dynamics of the charge-discharge process are reflected in the discharge time decreasing as the current density increases. The uniform form of the GCD curves for every composite shows optimal capacitive behavior in spite of the fluctuating current densities, demonstrating the materials' resilience and effectiveness under various operating circumstances. At a current density of 1 A/g, PRNS75 showed the highest specific capacitance of all the composites, measuring 675 F/g. The energy density values were determined based on the specific capacitance for binary composites having 207 F/g ,342F/g are 14.1 Wh/kg and 23.3 Wh/kg and power density values were determined 282 W/kg, 281 W/kg respectively.

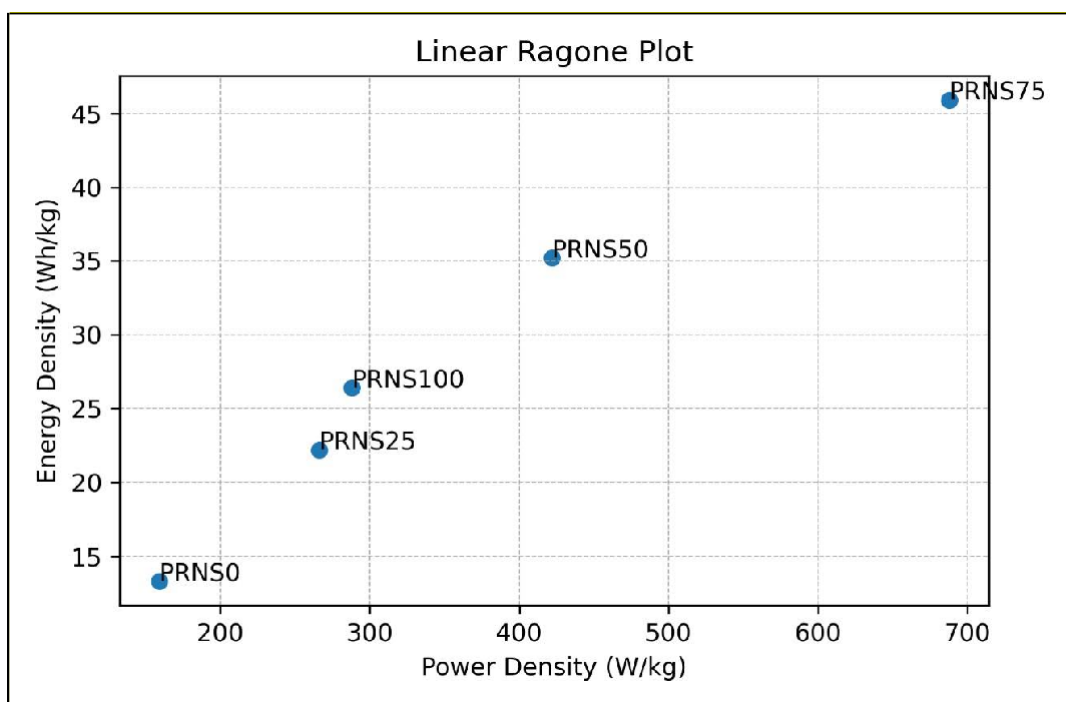


Fig.4.5.10 Ragone Plot

$$E = \frac{C_p(\Delta V)^2}{2} \quad (\text{Energy Density})$$

$$P = \frac{E}{\Delta t} \quad (\text{Power Density})$$

Table 4.5.5 Energy Density and Power Density of PRNS composite

Composite	Specific Capacitance (F/g)	Energy Density (Wh/kg)	Power Density (W/kg)
PRNS0	196	13.3	159
PRNS25	326.3	22.2	266
PRNS50	517.1	35.2	422
PRNS75	675	45.9	688
PRNS100	388.3	26.4	288

The energy density and power density values for PRNS75 were determined based on the specific capacitance 675 F/g , 45.9 Wh/kg and 688 W/kg respectively.

This improved performance is mostly attributable to the composite's well-balanced composition, where rGO guarantees superior conductivity and PPy offers a porous structure that makes electrolyte access simple. The integration of polypyrrole, rGO, and Ni-SrFe₂O₄ leads to enhanced charge storage capabilities, prolonged discharge durations, and consistent electrochemical performance, positioning this material as a strong contender for future energy storage solutions.

4.5.3 EIS Analysis

Electrochemical Impedance Spectroscopy (EIS) is a strong and flexible method for studying charge transfer processes, interfacial resistance, and ion diffusion in devices that store and convert energy. A small alternating current (AC) signal at different frequencies is used to measure the impedance response of an electrode material. This gives us important information about the basic electrochemical processes that affect how well the material works. EIS is a very important tool for studying supercapacitors, batteries, fuel cells, and corrosion. Using an equivalent circuit to model the impedance data makes it possible to find important values like solution resistance (R_s), charge transfer resistance (R_{ct}), Warburg impedance (Z_w) for ion diffusion, and double-layer capacitance (C_{dl}). The Nyquist plot is a common way to show EIS data. It makes it easier to tell the difference between resistive and capacitive behaviors in electrochemical systems. EIS is very important for optimizing electrode materials, making devices more efficient, and making electrochemical energy storage systems more stable over time because it can analyze dynamic charge storage mechanisms. EIS is a good way to characterize the electrochemical behavior of supercapacitor electrode

materials, including their resistivity and capacitance. It was done to see how well electrode materials move charge at the interface between the electrode and the electrolyte. The Nyquist plots of the samples we made show high-frequency parts as semicircles and low-frequency parts as straight lines that go up and down. The linear parts show the diffusion resistance (Warburg resistance, W) of the electrolyte ions, and the semicircular arcs show the faradaic charge-transfer resistance of the electrode material. The point where the high frequency meets the Z' axis shows the resistance of the electrochemical system (R_s). This is because the electrode materials have their own resistance, and there is also resistance at the electrode-electrolyte interface. We used a similar circuit to fit the Nyquist plots. Adding PPy to rGO/Ni-Sr ferrite often made R_{ct} go up a lot, but R_s stayed about the same. This is because ternary hybrids with more PPy have more interfaces. This means that adding more PPy to rGO/Ni-Sr ferrite makes it easier for the hybrid to hold a charge, which improves its capacitive performance[139,140].

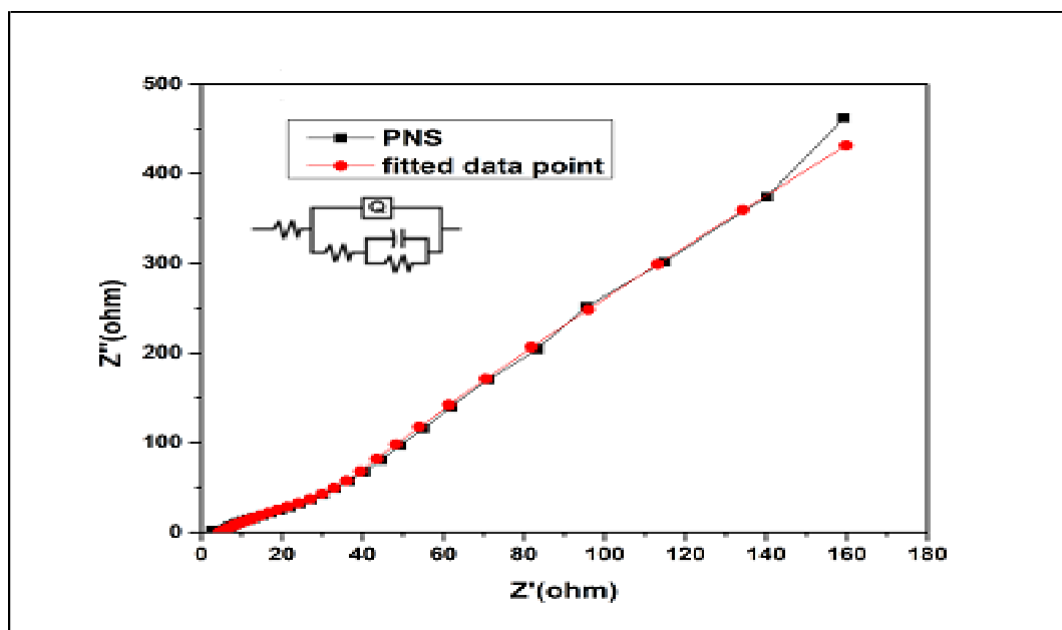


Fig. 4.5.9: Nyquist plot of PPy/Ni-SrFe₂O

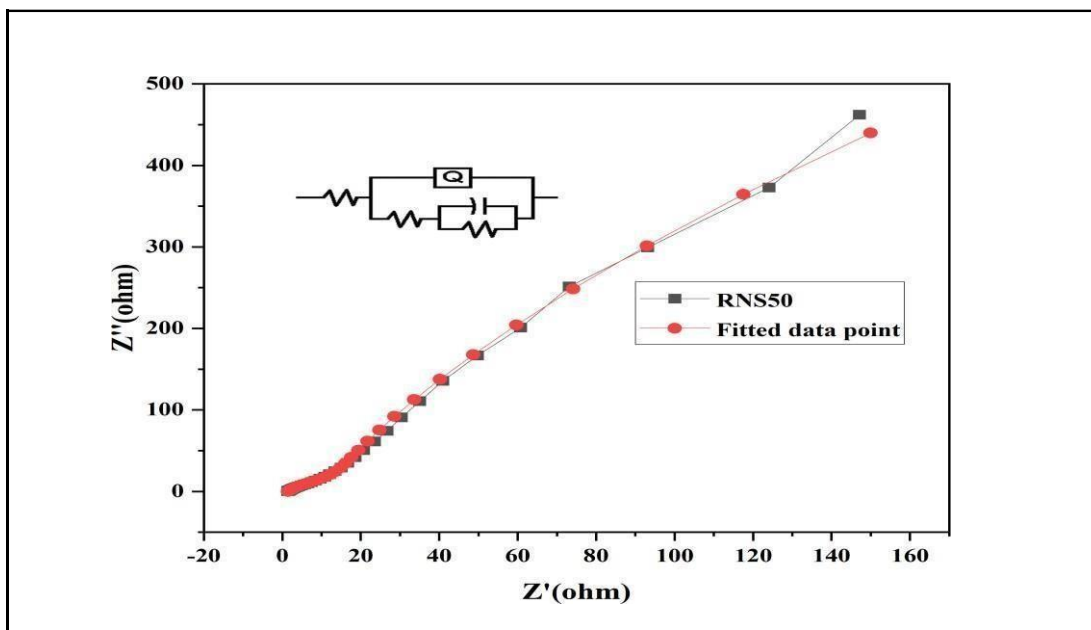
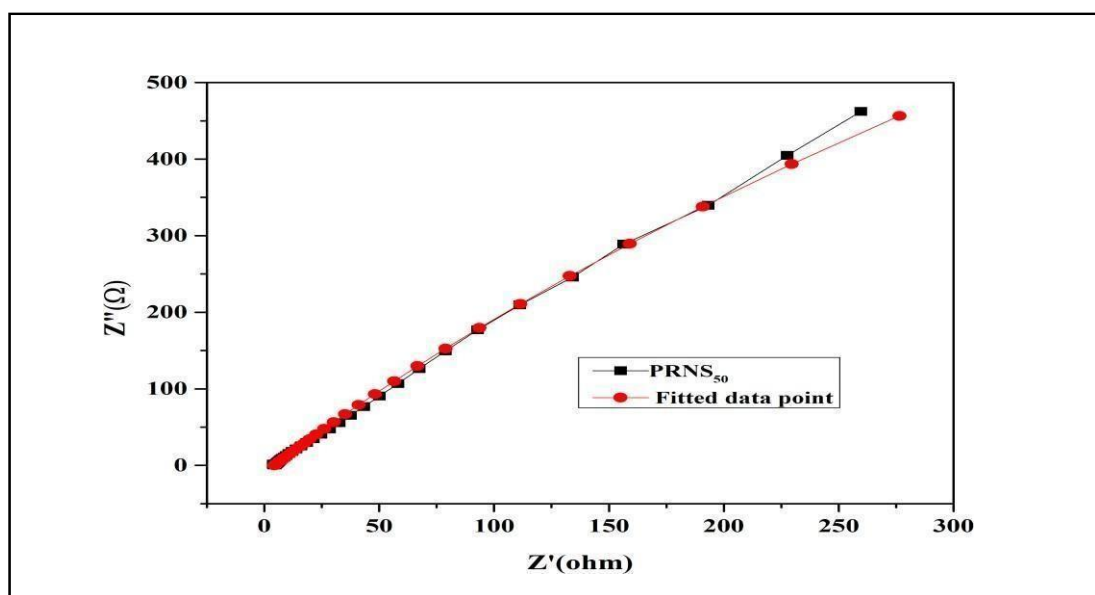


Fig.4.5.10 Nyquist plot of rGO/Ni-SrFe₂O₄



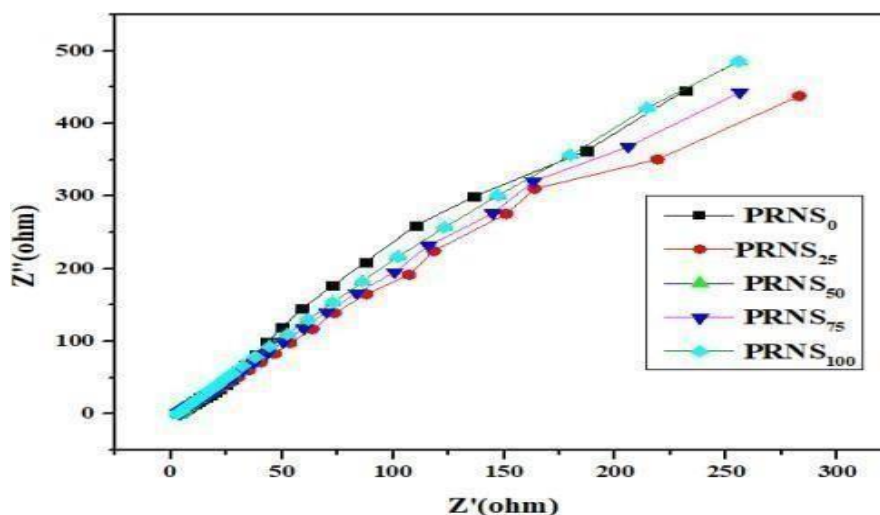


Fig.4.5.11 Nyquist plot of PPy/rGO/Ni-SrFe₂O₄

EIS was performed on PPy/Ni-SrFe₂O₄ in a 3M KOH electrolyte solution across a broad frequency range of 10^5 to 10^{-1} Hz to assess its charge storage efficiency and ion transport dynamics. The Nyquist plot illustrated offers essential insights into the electrochemical behavior of the electrode. A semicircle observed in the high-frequency region signifies the charge transfer resistance, reflecting the interaction between electrolyte ions and the electrode surface. The semicircle represents the solution resistance, reflecting the inherent resistance of both the electrolyte and the electrode material. A smaller semicircle indicates reduced charge transfer resistance, showcasing improved ion mobility and enhanced kinetics of electrochemical reactions within the electrode. Furthermore, a linear region that extends into the lower frequency domain is associated with Warburg impedance which signifies the diffusion of ions within the electrode material. The Warburg region offers significant insights into ion diffusion-controlled processes, essential for enhancing supercapacitor performance. **$R_s = 4.54 \, \Omega$ and $R_{ct} = 23 \, \Omega$** , for rGO/Ni-SrFe₂O₄ and **$R_s = 3.9 \, \Omega$, $R_{ct} = 16 \, \Omega$** , for PPy/Ni-SrFe₂O₄. In ternary composite PRNS75: Smallest semicircle ($R_{ct} = 24 \, \Omega$, $R_s = 4 \, \Omega$), indicating superior charge transfer and ion transport; best performance among all ratios confirming efficient charge transfer at electrode/electrolyte interface. The slope in this region indicates a blend of diffusion and capacitive behavior, which plays a significant role in the enhanced energy storage capacity of the PPy/rGO/Ni-SrFe₂O₄ composite. Nonetheless, the lack of a completely vertical line in the low-frequency range indicates that the system demonstrates characteristics of both pseudocapacitance and EDLC, rather than

exhibiting solely capacitive behavior. The delineated semicircle observed at elevated frequencies indicates the electrode's minimal charge transfer resistance, suggesting outstanding electrical conductivity and effective electron transport. The observed low resistance is a result of the combined influence of the polypyrrole matrix, which significantly boosts electrical conductivity, alongside the inclusion of rGO, which offers an extensive surface area for ion adsorption and charge accumulation. Furthermore, the Ni-SrFe₂O₄ component plays a significant role in enhancing the redox-active sites, thereby boosting the overall electrochemical performance of the electrode. The integration of these materials leads to enhanced electron and ion mobility, which facilitates greater specific capacitance and improved energy storage efficiency.

Table 4.5.6 Parameter value from the comparable circuit with fitting impedance for binary and ternary electrodes.

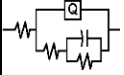
Sample	R _{ct}	Q	R _s	C
RNS	1.484	0.003393	127.7	1.352E-6
PNS	4.54	0.003204	1.142E4	8.371E-5
PRNS	3.919	0.002783	1.478E4	0.03908

Table 4.5.7 Parameter value from the comparable circuit with fitting impedance for the ternary electrode with varying ratio of Ni and Sr

Rs: Solution Resistance

Rct: Charge Transfer Resistance

Q: Constant phase element

Sample	R ₁	Q	R ₂	C
				

PRNS₀	3.744	0.003002	1.319E-8	0.000195
%Error	7.207	5.812	4.677E9	105.4
PRNS₂₅	4.899	0.002675	706.8	3.516E-5
PRNS₅₀	4.368	0.002473	3760	0.004349
PRNS₇₅	3.919	0.002783	1.478E4	0.03908
PRNS₁₀₀	3.235	0.002503	9005	2.661E-5

PRNS75 shows best balance between conductivity and diffusion. The EIS analysis indicates that the PPy/rGO/Ni-SrFe₂O₄ electrode demonstrates low internal resistance, effective charge transfer, and outstanding capacitive behavior, positioning it as a strong candidate for high-performance supercapacitors. PRNS75: Smallest semicircle (R_{ct} = 24 Ω, R_s = 4Ω), indicating superior charge transfer and ion transport; best performance..The impedance characteristics of the electrode underscore its suitability for use in energy storage systems, which demand rapid charge-discharge cycles and enduring electrochemical stability.

4.6 Electrochemical Study

The electrochemical properties of rGO/Ni-SrFe₂O₄ and PPy/Ni-SrFe₂O₄ electrodes are evaluated using CV, GCD, and EIS. These analyses provide insights into the charge storage mechanisms, capacitance retention, and ion diffusion efficiency of the electrodes. rGO/Ni-SrFe₂O₄ electrodes exhibit excellent electric double-layer capacitance (EDLC) behavior due to the high surface area and conductivity of rGO. Meanwhile, the presence of Ni-Sr ferrite enhances redox activity, leading to improved pseudocapacitive performance. On the other hand, PPy/Ni-SrFe₂O₄ electrodes demonstrate superior electrochemical stability and higher specific capacitance due to the synergistic effect of PPy's conjugated polymer structure and the redox-active sites of Ni-Sr ferrite. The integration of polypyrrole, rGO, and Ni-Sr ferrite into a ternary electrode material has shown remarkable improvements in energy storage performance. The combination of these materials results in enhanced charge transfer, improved capacitance, and long-term stability.

The electrochemical study of polypyrrole/rGO/Ni-Sr ferrite electrodes reveals that:

- The hybrid structure allows for efficient ion transport and charge redistribution.
- The presence of rGO reduces charge transfer resistance and enhances conductivity.
- Ni-Sr ferrite contributes to the pseudocapacitive behavior, increasing energy density.
- Polypyrrole ensures flexibility and mechanical stability, preventing electrode degradation over multiple cycles.

Table 4.6.1 Synergistic contribution of each component in composites

Composite	Components	Functionality of Each Component	Key Properties	Electrochemical Behavior
PPy/Ni-SrFe ₂ O ₄	Polypyrrole + Nickel-Strontium Ferrite	PPy: Provides high conductivity and pseudocapacitance - Ni-SrFe₂O₄: Adds electrochemical Activity	Enhanced pseudocapacitance Moderate surface area Synergistic redox activity	Good specific capacitance, Stable charge/discharge behavior
rGO/Ni-SrFe ₂ O ₄	Reduced Graphene Oxide + Nickel-Strontium Ferrite	rGO: Provides a large surface area and double-layer capacitance Ni-SrFe ₂ O ₄ : provides active sites for redox reactions	High surface area, improved conductivity, and enhanced ion transport.	Higher rate capability - Faster electron transport - Better cycling stability
PPy/rGO/Ni-SrFe ₂ O ₄ (Ternary Composite)	PPy+ rGO + Ni-SrFe ₂ O ₄	Combines the benefits of rGO (double-layer), PPy(pseudo), and Ni-SrFe ₂ O ₄ (electroactive ferrite)	High conductivity, excellent synergistic effect, high specific surface area, and strong electrochemical activity	Highest specific capacitance - Good cyclic stability - Balanced pseudocapacitive and EDLC behavior

These attributes make PPy/rGO/Ni-SrFe₂O₄ electrodes highly promising for use in high-performance Energy storage Devices. Future research should focus on optimizing the synthesis parameters and exploring new hybridization strategies to further enhance energy storage efficiency.

Table4.6.2 Comparison of rGO/NiSrFe₂O₄ and PPy/rGO/NiSrFe₂O₄ with previously reported materials

Sr No.	Electrode	Scan rate	Electrolyte	Csp (Fg ⁻¹)	Reference
1.	CNT/PPy/MnO ₂	20mV/s	1M Na ₂ SO ₄	281	[33]
2.	rGO/NiCoFe ₂ O ₄	10mV/s	3M KOH	157	[34]
3.	rGO/NiFe ₂ O ₄	10mV/s	1M KOH	584.6	[28]
4.	PPy/rGO/NiCoFe ₂ O ₄	10 mV/s	3M KOH	210	[34]
5.	rGO/Ni-SrFe ₂ O ₄	10mV/s	3M KOH	516	This work
6	PPy/Ni-SrFe ₂ O ₄	10mV/s	3M KOH	654	This work
7	PPy/rGO/Ni-SrFe ₂ O ₄	10mV/s	3M KOH	710	This work

Chapter 5

(Summary and Conclusion)

5.1 Summary

This study presents the successful synthesis and characterization of polypyrrole (PPy)-doped reduced graphene oxide (rGO)/Ni-Sr ferrite nanocomposites, focusing on their potential application as electrode materials in energy storage devices. The thorough structural, morphological, and electrochemical analyses revealed that the synthesized nanocomposites exhibit exceptional properties, positioning them as strong contenders for supercapacitor electrodes. The structural analysis via X-ray diffraction (XRD) confirmed the successful integration of Ni-Sr ferrites within the rGO matrix, while Fourier-transform infrared spectroscopy (FTIR) affirmed the presence of PPy functional groups, which played a role in improving conductivity and electrochemical performance. The morphological evaluations performed through scanning electron microscopy (SEM) demonstrated a well-dispersed and interconnected network, enhancing charge transport and electrochemical interactions.

The synthesized composites were subjected to electrochemical characterization through CV, GCD and EIS to assess their charge storage capabilities. The analysis indicated that the PPy-doped rGO/Ni-Sr ferrite nanocomposite displayed remarkable electrochemical performance, showcasing high specific capacitance, excellent rate capability, and long-term cycling stability, all of which are essential for practical energy storage applications. The exceptional performance of this composite can be linked to the synergistic interaction among PPy, rGO, and Ni-Sr ferrites. PPy improves electrical conductivity and offers a flexible polymeric framework for charge transport. Reduced graphene oxide (rGO) enhances surface area and facilitates rapid ion diffusion, thereby improving double-layer capacitance. In the meantime, Ni-Sr ferrite demonstrates enhanced redox activity, which significantly improves pseudocapacitive behavior. The combination leads to improved electrochemical stability and energy storage efficiency, positioning the nanocomposite as a strong contender for cutting-edge supercapacitor and battery applications. Moreover, the incorporation of rGO significantly minimized the

aggregation of ferrite nanoparticles, promoting uniform dispersion and enhancing the electrochemically active surface area. The addition of PPy led to enhanced electrical conductivity and pseudocapacitive behavior, thereby improving the overall energy storage performance. The optimized nanocomposite demonstrated a well-balanced integration of electric double-layer capacitance and pseudocapacitive behavior, positioning it as a strong contender for hybrid energy storage systems. The cyclic stability tests demonstrated that the material maintained a considerable portion of its initial capacitance even after extensive charge-discharge cycles, underscoring its robustness and suitability for real-world applications. Furthermore, the low internal resistance demonstrated through impedance spectroscopy studies further confirmed the appropriateness of the synthesized nanocomposites for supercapacitor applications. Simple, eco-friendly, and scalable techniques for producing binary composite electrodes have been established for application in energy storage devices.

5.2 Conclusion

The electrodes consist of $\text{NiSrFe}_2\text{O}_4$ and the conductive polymer PPy. The synthesis of PPy/ MeFe_2O_4 (Me=Ni, Sr) composites is straightforward and can be accomplished in a single step, which enhances their potential for large-scale production. The findings validate the efficacy of our synthesis process in producing synergistic composite electrode materials. This approach provides a promising avenue for the advancement and alteration of the characteristics of high-performance energy storage devices. The incorporation of metal ferrite and PPy enhances the active surface area, with PPy functioning as a conductive network that boosts the electrochemical activity and active sites of Ni-Sr Fe_2O_4 . From the CV curve, the specific capacitance of binary composite rGO/Ni-Sr Fe_2O_4 was found to be 516 F/g, and for PPy/ Ni-Sr Fe_2O_4 was determined to be 654 F/g at a scan rate of 10 mV/s. Consequently, the core-shell material electrode has been validated to demonstrate exceptional capacitive performance. The incorporation of polypyrrole markedly improved charge storage efficiency, elevating the specific capacitance from for PPy/rGO/NiSr ferrite to 710 F/g. Additionally, from GCD measurement, the composite rGO/Ni-Sr Fe_2O_4 showed a specific capacitance of 207F/g and PPy/Ni-Sr Fe_2O_4 showed a specific capacitance of 342F/g at 1A/g, whereas the ternary composite PPy/rGO/Ni-Sr Fe_2O_4 revealed a specific capacitance of 675F/g at the same current density of 1A/g. The enhancement observed can be linked to the inhibition of graphene layer reattachment, along with the synergistic interaction

between metal ferrite and PPy, which boosts charge transfer and electrochemical activity. In conclusion, a high-performance electrode material for supercapacitors has been successfully synthesized through the sol-gel auto-combustion technique, followed by chemical oxidative polymerization. Several ternary composites of PPy/rGO/Ni-SrFe₂O₄ were created for this study, and their potential as high-performance electrode materials for supercapacitors was methodically assessed. We were able to examine how composition affected these composites' electrochemical performance by adjusting the nickel and strontium concentration from 0% to 100%. The structural and electrochemical characteristics of the synthesized materials have been thoroughly revealed by the results of XRD, FTIR, FESEM, and electrochemical characterization methods as CV, GCD, and EIS. To summarize, a high-performance electrode material for supercapacitors has been created utilizing polypyrrole and rGO doped Ni-Sr substituted ferrite, which was produced using the sol-gel auto-combustion technique. The findings of the experiment demonstrated that Ppy/rGO/Ni-SrFe₂O₄ nanocomposite has a maximum specific capacitance of 900F/g for the combination of PRNS75 at a scan rate of 10mV/s. GCD specific capacitance was calculated to be 675F/g for PRNS75 at 1A/g current density in 3M KOH. The ternary composite PRNS75 (PPy/rGO/Ni-SrFe₂O₄) showed superior electrochemical performance with a specific capacitance of 900.7F/g, energy density of 46 Wh/kg, and power density of 688W/kg due to its optimized Nickel-Strontium content, facilitating efficient charge transfer and ion diffusion. Conversely, excessive ferrite content in PRNS100 leads to particle agglomeration and reduced electrical conductivity, which hinders electron transport and limits electrolyte ion diffusion. The findings indicate that the PPy/rGO/Ni-Sr ferrite composite stands out as a promising option for energy storage applications, showcasing exceptional conductivity, elevated capacitance, and enduring stability. Among all the synthesized materials, PRNS75 exhibited the most outstanding electrochemical performance, making it a highly promising candidate for Energy storage applications.

5.3 Future Scope

To make commercial energy storage devices more useful, future research should look into optimization strategies, different doping elements, and large-scale fabrication methods. More research and progress in this area could make it possible to use this composite material in real-world energy storage solutions. The results of this study show that it is possible to successfully combine reduced graphene oxide metal- doped iron oxide, and conductive polymers like polypyrrole to make high- performance supercapacitor electrodes. Using these materials together can improve electrochemical properties like specific capacitance, conductivity, redox activity, and cycling stability. This method is a very good way to design and improve advanced energy storage systems. The successful combination of graphene, metal-doped iron oxide, and conductive polymers shows that supercapacitor electrode materials could be made in large quantities, at a low cost, and with high performance. This is a big step forward for energy storage technologies in the future. This study shows PPy/rGO/Ni- Sr ferrite composites could be used as cutting-edge electrode materials in next- generation energy storage devices. The combination of conductive polymers, graphene- based materials, and ferrite nanoparticles creates a platform that can be used for many things, including high-performance supercapacitors and batteries. Future research should focus on optimizing synthesis conditions, finding new dopants, and figuring out how to make things on a large scale. The findings of this study add to the growing body of work on hybrid nanocomposites as effective and long-lasting ways to store energy. There needs to be more research in a number of important areas because of the changes in the materials used for electrodes in energy storage devices. Future research may focus on optimizing synthesis parameters, exploring dopants, and analyzing device-level performance to make them more useful for commercial supercapacitor technologies. This study adds to the ongoing work on energy storage materials by providing a scalable and cost-effective way to make high-performance electrode materials with multiple functions. This study's findings make it possible to create new hybrid nanocomposites for a variety of electrochemical applications, including hybrid energy storage devices, batteries, and supercapacitors. Future research on PPy/rGO/Ni-Sr ferrite composites should focus on making them as scalable and electrochemically efficient as possible for use in businesses.

- 1. Optimization of Synthesis Parameters:** To get the highest possible electrochemical efficiency, the conditions of the synthesis can be fine-tuned. The reaction temperatures, the polymerization time, and the concentrations of the dopant are all examples of these conditions. We can use advanced modeling tools to guess what the best synthesis conditions would be to get the most energy storage capacity.
- 2. Alternative Dopants and Functionalization:** By looking into more dopants, like transition metal oxides, conductive nanofibers, or heteroatom doping, it may be possible to make the composite's charge transport and electrochemical properties even better. Adding materials that are both biocompatible and good for the environment can make it more useful and open up more uses for it in the fields of wearable technology and medicine.
- 3. Large-Scale Fabrication and Commercialization:** Scaling up the synthesis process while keeping the material's structure and electrochemical performance intact is a big problem. It is suggested that future work focus on finding ways to make composite electrodes on a large scale that are both good for the environment and cheap.
- 4. Integration into Hybrid Energy Storage Systems:**

It might be possible to build high-energy-density devices that can charge and discharge quickly by combining PPy/rGO/Ni-SrFe₂O₄ composites with other energy storage technologies like lithium-ion batteries or hybrid supercapacitors. To make real progress in portable and wearable electronics, we need to look into how to use these composites in devices that are flexible, light, and have a lot of power in a small space.
- 5. Long-Term Stability and Durability Studies:** It is important to test the long-term electrochemical stability, cycle life, and environmental endurance of these composites for practical uses. To improve cycle life and performance retention over long periods of use, future research should focus on understanding how to optimize electrode designs and improve the interactions between electrolytes and electrodes.
- 6. Exploring Alternative Electrolytes and Configurations:** To make energy storage operations even more efficient, more research needs to be done on the

effects of different electrolytes, such as ionic liquids and solid-state electrolytes. Also, researchers can look into asymmetric and hybrid electrode topologies to see if they can make them work better for certain uses. Some of these uses are grid storage, electric cars, and combining renewable energy sources.

Limitations of the Present Study:

While the current work shows that PPy/rGO/Ni-Sr ferrite composites have promising electrochemical performance as supercapacitor electrode materials, some constraints still exist:

1.Restricted synthesis parameter:The generated composite compositions are the primary focus of the study; nevertheless, thorough optimization of the reaction temperature, polymerization time, dopant concentration, and synthesis conditions was not thoroughly investigated.

2.Limited choice of dopants: Only Ni-Sr dual-doped ferrite is covered in this paper. Transition metal oxides, heteroatom-functionalized systems, and other potential dopant combinations were not examined for comparison.

3.Fabrication at the laboratory scale: Laboratory-scale synthesis and testing of the electrode materials took place. The viability of industrial processing, large-scale manufacture, and cost analysis were not thoroughly investigated.

4.Limited validation at the device level: The electrode/material level was where the electrochemical performance was primarily assessed. For practical application, more testing is needed in full-cell, asymmetric, flexible, or hybrid supercapacitor topo

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7.List of publications

1. Green Battery: Sustainable Way of Energy Storage (Book chapter, Book- Electrocatalytic Materials, Springer Nature)
2. Metal Ferrites and their Synthesis Techniques for Energy Storage Devices: A Review(AIP Proceedings)
3. Sol-Gel Auto-Combustion Synthesis of Strontium Ferrite Nanoparticle with Reduced Graphene Oxide Hybrid Nanocomposite Electrode: A Synergistic Improvement of Supercapacitive Performance (Topics in Catalysis)
4. Unlocking Enhanced Electrochemical Mechanisms towards High-Performance Supercapacitor Electrodes: Synergistic Mechanisms of Reduced Graphene Oxide, polypyrrole conducting Polymer and Ni- Sr ferrite for Next-generation Energy Storage(Pure And Applied Chemistry)
5. Synergistic Mechanisms in the facile synthesis of Polypyrrole conducting Polymer Doped Nickel-Strontium Ferrite Nanocomposites: Advanced Electrochemical Properties for high-performance energy storage applications(Communicated)
6. Advanced Polypyrrole/rGO/Ni-SrFe₂O₄ (PRNS) nanocomposite Electrode for high-energy-densityElectrochemical Storage(Communicated)

Conference Presentations

1. Metal ferrites and their synthesis techniques for energy storage devices: A Review in 4th International Conference on “Recent Advances in Fundamental and Applied Sciences (RAFAS-2023) held from 24-25 March 2024
2. Fabrication of rGO doped Ni-SrFe₂O₄ (RNSF) composite for use as an active electrode in energy storage systems in 5th International Conference on Recent Advances in Fundamental and Applied Sciences (RAFAS-2024) held from 19-20 April 2024