INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ORIGINAL ARTICLE

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OPEN ACCESS

Received: 03/11/2025

Accepted: 09/12/2025

Published: 31/12/2025

Citation: Aiman SI, Naveen Kumar JR, Rohit M, Basavannavar DR, Praveen BM, Dhananjay KP, Govindarajan S, Nagaraju G, Devendra BK (2025) Green Synthesis of $MnMoO_4$ Nanoparticles Using *Salvia hispanica* Seed Powder for Electrochemical Urea Sensing and Supercapacitor Applications. Indian Journal of Science and Technology 18(48): 3863-3869. https://doi.org/10.17485/IJST/v18i48.1784

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN

Print: 0974-6846

Electronic: 0974-5645

Green Synthesis of $MnMoO_4$ Nanoparticles Using *Salvia hispanica* Seed Powder for Electrochemical Urea Sensing and Supercapacitor Applications

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Abstract

Objectives: Manganese molybdate ($MnMoO_4$) nanoparticles were synthesised by using an eco-friendly combustion approach. These are used as sensor for detecting urea. **Methods:** $MnMoO_4$ nanoparticles were synthesized by comburstion of a green precursor solution containing *Salvia hispanica* seed powder. Scanning Electron Microscopy (SEM) was used to characterise the morphology of the nanomaterails. Glassy Carbon Electrode (GCE) was modified by using developed $MnMoO_4$ nanoparticles. Electrochemical studies were conducted such as Cyclic Voltammetry (CV), Linear Sweep Voltammetry (LSV), and Electrochemical Impedance Spectroscopy (EIS). Charge discharge tests were conducted using a nickel foam-coated electrode. **Findings:** SEM analysis revealed porous, aggregated nanoparticle structures. EIS studies shows that Rs and R_{ct} values of 2.667 Ω and 1.628 Ω, respectively, indicating efficient charge transfer and successful electrode modification. In CV studies, the anodic peak current (I_{pa}) increased from 0.014 μA to 0.100 μA, confirming enhanced electrochemical activity, Linear relationship was found in LSV studies The NMO electrode has a specific capacity of 71.94 $C{\cdot}g^{-1}$ at a current density of 2.5 $A{\cdot}g^{-1}$. shows good energy storage application. **Novelty:** Existing studies on transition-metal molybdates mainly use hydrothermal or high-temperature

chemical routes that are costly and environmentally taxing, with $MnMoO_4$ mostly explored for supercapacitors rather than urea sensing. In contrast, this work presents a simple, low-cost green combustion method using *Salvia hispanica* seed powder, yielding $MnMoO_4$ nanoparticles with excellent charge-transfer properties (R_s = 2.667 Ω, R_{ct} = 1.628 Ω) and high sensitivity toward low-concentration urea (10 μM). This approach broadens the application of $MnMoO_4$ while offering a greener and more efficient synthesis route.
Keywords: $MnMoO_4$; Sensor; Cyclic voltammetry; Charge and Discharge studies

1 Introduction

The green synthesis of $MnMoO_4$ nanoparticles offers key advantages, as it avoids hazardous chemicals and high-temperature routes, reducing environmental pollution and chemical waste. Using natural precursors like *Salvia hispanica* seed powder minimizes the need for synthetic stabilizers while enabling a rapid, low-energy, and cost-effective combustion process. This method produces highly porous nanostructures with improved morphology and surface functionalization due to natural polymers and phytochemicals. It is easily scalable, reproducible, and yields biocompatible materials suitable for urea sensing and other biomedical applications. Urea plays a vital role across multiple industries, including food processing, polymer manufacturing, pharmaceuticals, and agriculture[(1)]. In the dairy sector in particular, highly sensitive and selective urea detection systems are essential to ensure product safety and prevent adulteration. Beyond industrial use, urea also serves as a fertilizer, de-icing agent, and stabilizing component in detergents and soaps[(2)]. However, the long-term and excessive use of urea-containing products can lead to its accumulation in soil and water, causing environmental concerns such as eutrophication, soil acidification, and ecosystem imbalance. Elevated urea levels also pose toxicological risks to humans and animals. Typically, human blood contains 2.6–6.5 mM urea, while urine contains far higher concentrations, averaging 342 ± 67 mM depending on hydration levels and metabolic conditions. Therefore, the development of highly sensitive and selective urea sensors is crucial for monitoring environmental samples, food products (such as milk), and biological fluids like blood and urine[(3)].

In parallel, recent research has focused on transition metal oxides integrated with carbon-based materials as promising electrode candidates for high-performance supercapacitors due to their cost-effectiveness, environmental friendliness, and non-toxic nature[(4)],[(5)]. The multiple oxidation states of these oxides enhance their electrocatalytic activity, redox behavior, and charge-storage capabilities. Particularly, binary and ternary metal oxides have attracted attention because they often exhibit superior electrical conductivity and electrochemical performance compared to their single-metal-oxide counterparts[(6)]. Among these, molybdenum-based binary oxides such as $CoMoO_4$, $NiMoO_4$, $FeMoO_4$, and $Cu_3Mo_2O_9$ have demonstrated excellent catalytic and energy-storage properties[(7)]. For example, $NiMoO_4/CoMoO_4$ nanorods synthesized via hydrothermal methods delivered a high specific capacitance of 1445 F g^{-1} at 1 A g^{-1} in 1 M KOH[(8)], while MoO_3 nanorods achieved 175 F g^{-1} at 2 mA g^{-1} in 1 M Na_2SO_4[(9)].

Despite this progress, the extract of *Salvia hispanica* (chia) seed acts as a natural reducing, capping, and stabilizing agent in the green combustion synthesis of $MnMoO_4$ nanoparticles. Its polysaccharides, proteins, and polyphenols decompose during heating to reduce metal ions, while simultaneously coating the growing particles to prevent agglomeration and ensure uniform morphology. The mucilage-rich polysaccharide matrix provides steric stabilization and promotes porosity through gas release during combustion. This biomolecule-assisted process enables controlled nanoparticle formation and improved electrochemical performance without the need for synthetic surfactants or toxic reducing agents. $MnMoO_4$ remains a significantly underexplored electrode material, even though it possesses a high theoretical capacity of 874 mAh g^{-1}[(10)],[(11)]. Only limited studies have investigated its electrochemical behavior, and the existing data remain insufficient to fully understand its charge-storage mechanisms, conductivity properties, and suitability for practical supercapacitor applications. This lack of systematic investigation represents a clear research gap.

To address this gap, the present study aims to explore the structural, electrochemical, and capacitive characteristics of $MnMoO_4$ synthesized through a green approach, and to evaluate its feasibility as a high-performance electrode material for next-generation supercapacitors. This work provides a new insight into the potential of $MnMoO_4$ and contribute to the development of efficient, sustainable, and high-capacity energy storage devices. The enhanced performance in this study arises from the green combustion synthesis using *Salvia hispanica* seed powder, which generates $MnMoO_4$ nanoparticles with higher porosity, more active sites, and better surface accessibility than those produced by conventional hydrothermal or chemical methods. The natural polysaccharides in the seed powder enable controlled combustion, yielding a porous structure that improves ion diffusion and electrochemical kinetics. This is evident from the low R_s (2.667 Ω) and R_{ct} (1.628 Ω) values, which outperform many reported $MnMoO_4$ materials. The porous nanostructure also increases the redox-active surface area, resulting in higher anodic peak currents and superior sensitivity for detecting low urea concentrations (10 μM). Unlike previous studies focused mainly on energy storage, this work demonstrates $MnMoO_4$ provides faster electron transport, enhanced surface area, better stability, and dual-functionality (sensing + supercapacitors), making it unique and highly efficientboth excellent conductivity and effective urea sensing, offering a more sustainable and efficient alternative to existing $MnMoO_4$ based technologies.

2 Materials and Methods

2.1 Materials

Salvia hispanica, the chia plant, seeds were bought from Tumakuru, Karnataka, India. Ammonium molybdate and manganese nitrate hexahydrate were supplied by Merck. Every chemical was utilized just as it was delivered, requiring no additional purification.

2.2 Synthesis of Nanoparticles (NPs)

S. hispanica seeds were ground into a fine powder and used as a green fuel for synthesis. The seed powder, ammonium molybdate, and manganese nitrate hexahydrate were mixed in a 1:1 ratio with 10 mL of distilled water and stirred for 10 minutes. The mixture was combusted in a muffle furnace at 500 °C, cooled, and the obtained product was ground and calcined at 600 °C for 3 hours to get $MnMoO_4$ nanoparticles.

2.3 Preparation of Modified Glassy Carbon Electrode with $MnMoO_4$ Nanoparticles

The GCE surface was polished carefully with alumina powder on a polishing cloth. The polished electrode was then ultrasonicated in ethanol to remove residual particles. The $MnMoO_4$ nanoparticle suspension was coated onto the cleaned electrode surface using the drop-casting method and dried at room temperature.

2.4 NPs-Coated Nickel Foam Preparation

A piece of nickel foam (1 cm^2) is used as the substrate. $MnMoO_4$ nanoparticles and graphite in a 30:70 weight ratio, using silicone oil as the binding agent, using a mortar and pestle to form a uniform paste. This paste was then coated as a thin layer onto the nickel foam and left to dry overnight at room temperature[12].

2.5 Characterization

Electrochemical measurements for biosensing applications were conducted using a Biologic SP-50e electrochemical workstation, while supercapacitor performance studies were carried out on a CHI 660 electrochemical analyzer.

2.6 Electrochemical Impedance Spectroscopy (EIS)

A sensitive analytical method for examining how an electrochemical system reacts to small-amplitude alternating current (AC) disturbances over a variety of frequencies is electrochemical impedance spectroscopy (EIS). EIS provides valuable insights into the system's structural properties, electrode/electrolyte interfaces, and the kinetics of electrochemical reactions.

2.7 Cyclic Voltammetry (CV)

Cyclic voltammetry, or CV, is a commonly used method for studying the interfacial electrochemical processes occurring at electrode surfaces under varying potential scans. By analyzing the shifts and shapes of current peaks, Electroactive species' redox behavior can be described. The electrolyte used for Urea sensing is few molar concentrations of urea chemical and pH 7 solution. This method also enables the quantitative analysis of analytes, such as herbicide concentrations[13].

3 Results and discussion

3.1 Morphological analysis

The SEM analysis reveals the morphology of the nanoparticles, as shown in Figure 1(a–b). The particles exhibit an irregular shape with noticeable agglomeration. The images provide morphological details across a size range of approximately 300 nm to 10 μm.

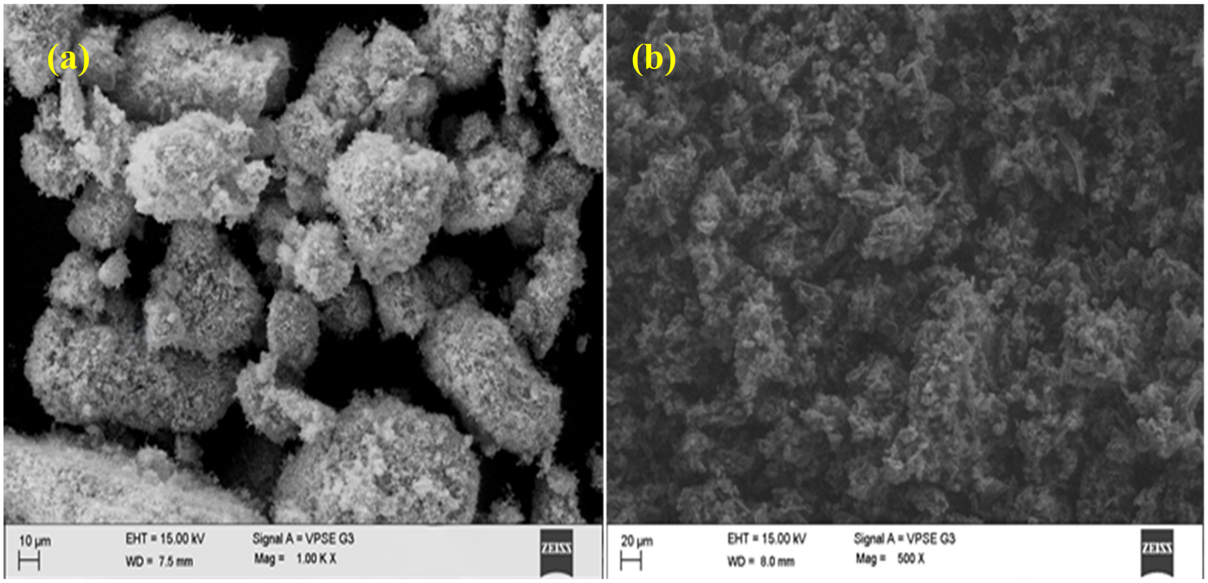

Fig 1. SEM images of $MnMoO_4$ NPs

3.2 Nano particles Electrochemical Analysis

3.2.1. Nanoparticle Electrochemical Impedance Spectroscopy:

The electrochemical performance of the synthesized NMO was evaluated using EIS in 0.1 M KCl with a 5 mV signal over 10 MHz–100 kHz. The Nyquist plots show that the NPs-modified GCE exhibited Rs and Rct values of 2.667 Ω and 1.628 Ω, respectively, indicating efficient charge transfer and successful electrode modification[14]. The results fit well with the $L_1 + R_1 + C_1/(Q_2 + R_2)$ Randles circuit model, confirming effective nanoparticle integration and improved electrochemical conductivity[15].

3.2.2. CuV/GCE cyclic voltammetry:

I–V measurements was performed using 10 micro molar urea in water to investigate the electro-chemical response of the modified electrode. Cyclic voltammetry (CV) was performed to assess the electrochemical behavior of the nanoparticle-modified GCE in 10 μM urea solution (Figure 2a). A rise in current with applied potential indicated urea oxidation and reduction. As the scan rate increased from 20 to 100 mV·s^{-1}, confirming enhanced electrochemical activity. This direct proportionality between I_{pa} and scan rate (v) across the 20–100 mV·s^{-1} range suggests a surface-controlled electrochemical process, as illustrated in Figure 2a[16]. Conversely, the cathodic as seen in Figure 2b, peak current (I_{pc}) dropped from -0.006 μA to -0.010 μA and was discovered to be inversely correlated with scan rate[17].

3.2.3. Urea linear sweep voltammetry:

To evaluate the electrocatalytic activity of modified electrode for urea solutions with concentrations between 25 and 120 μM were examined at a scan rate of 50 mV·s^{-1} in pure water. As illustrated in Figure 3a, the reduction peak current increased progressively from -0.070 μA to -0.100 μA with rising urea concentration, demonstrating the effective catalytic behavior of the electrode[18]. Peak current and urea concentration have a linear relationship is shown in Figure 3b. The fitted linear equation, ranging from I_{pc} = 0.383 μM to I_{pc} = 1.784 μM, exhibited a high correlation coefficient (R^2 = 0.9863) with a slope of y = 0.0596, indicating that the electrochemical reduction of urea at the $MnMoO_4$ modified electrode follows first-order kinetics[19].

3.2.4. Supercapacitor studies:

Cyclic voltammetry (CV) curves of the manganese molybdate electrode are presented in Figure 4a, showing distinct redox peaks characteristic of faradaic charge storage processes. The calculated specific capacitance (SC) values is 437.13 F·g^{-1}. The observed increase in SC is attributed to the addition of PVP surfactant, which promotes surface modification and enhances the electrochemical performance of the electrode[20]. Furthermore, compared to other molybdate-based electrodes, manganese

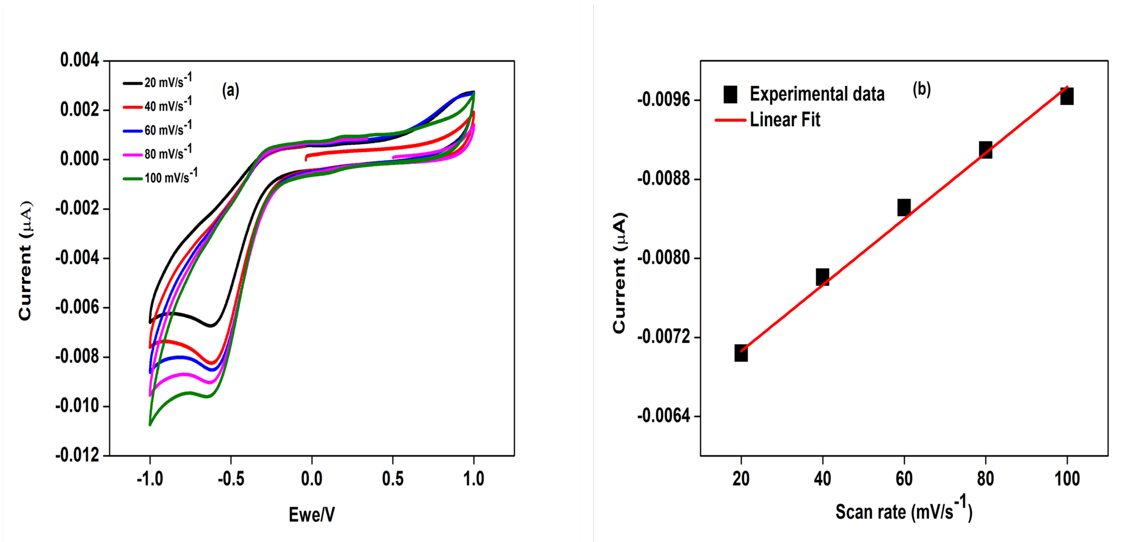

Fig 2. a) Cyclic voltammetry of NPs in distilled water for sensing of Urea with different scan rate. b) Optimization of oxidation and reduction peak from CV

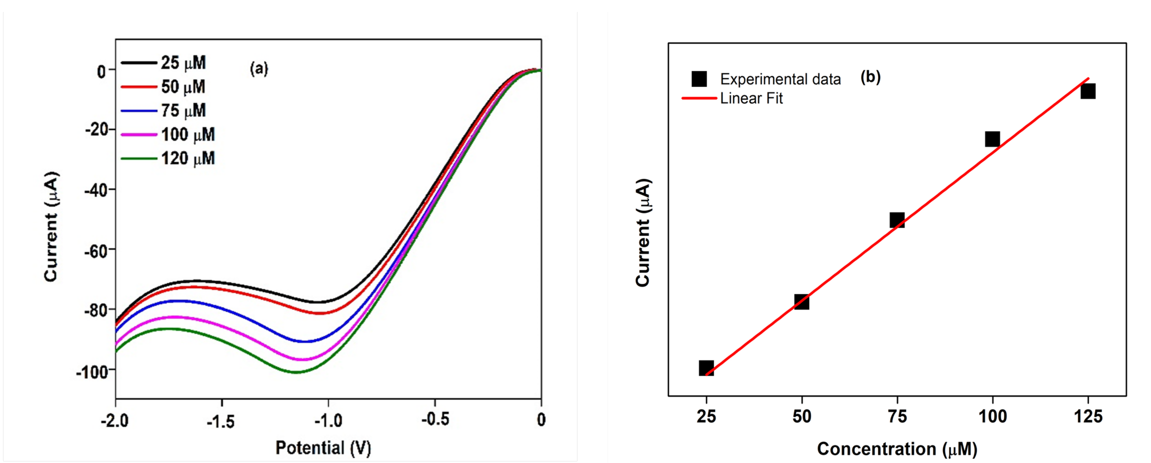

Fig 3. a) LSV data of NPs with different concentration of urea. b) Linear regration of LSV data with current vs concentration of urea

molybdate exhibits notably higher capacitance values, which can be ascribed to the incorporation of copper ions that improve charge storage capability[21]. The specific capacitance was calculated using the following formula.

$$Cs = \frac{1}{2mv(V2 - V1)} \int_{V1}^{V2} i(V)dV$$

In this analysis, m, υ, (V_2–V_1), and the active material's mass, the symbol i(V) represents the scan rate, potential window, and current at each potential[22]. The specific capacitance (Cs) is multiplied to obtain the specific capacity (Q, in C·g^{-1}). by the absolute potential window $|V_2 - V_1|$. For the MMO electrode, Cs was found to be 437.13 F·g^{-1}, corresponding to a specific capacity of 437.13 F·g^{-1} at 1 mV·s^{-1} scan rate[23]. However, the specific capacity decreases with increasing scan rates due to limited ion diffusion within the electrode material. Additionally, to further elucidate the charge storage mechanism, the method proposed by Dunn and colleagues was employed in this study[24].

Galvanostatic charge-discharge (GCD) experiments were was out to evaluate the electrodes' useful specific capacity. Figure 4(a) and (b) display the resultant GCD curves for NMO electrodes with varying current densities tested in 6 M KOH[25]. These curves indicate that faradaic redox reactions significantly contribute to the overall energy storage mechanism of the MMO electrode. The specific capacity was calculated using the following formula.

$$Q = (I * \Delta t)/m$$

Here, I, Δt, and m stand for the active electrode material's mass, discharge duration, and applied current, respectively. The MMO electrode has a specific capacity of 437.13 F·g^{-1} at a current density of 2.5 A·g^{-1}. Limited ion diffusion at higher rates is the reason for the decrease in specific capacity as current density rises[26]. Additionally, the cyclic performance of the NMO electrodes was evaluated using galvanostatic charge–discharge (GCD) measurements at a current density of 2.5 A·g^{-1}.

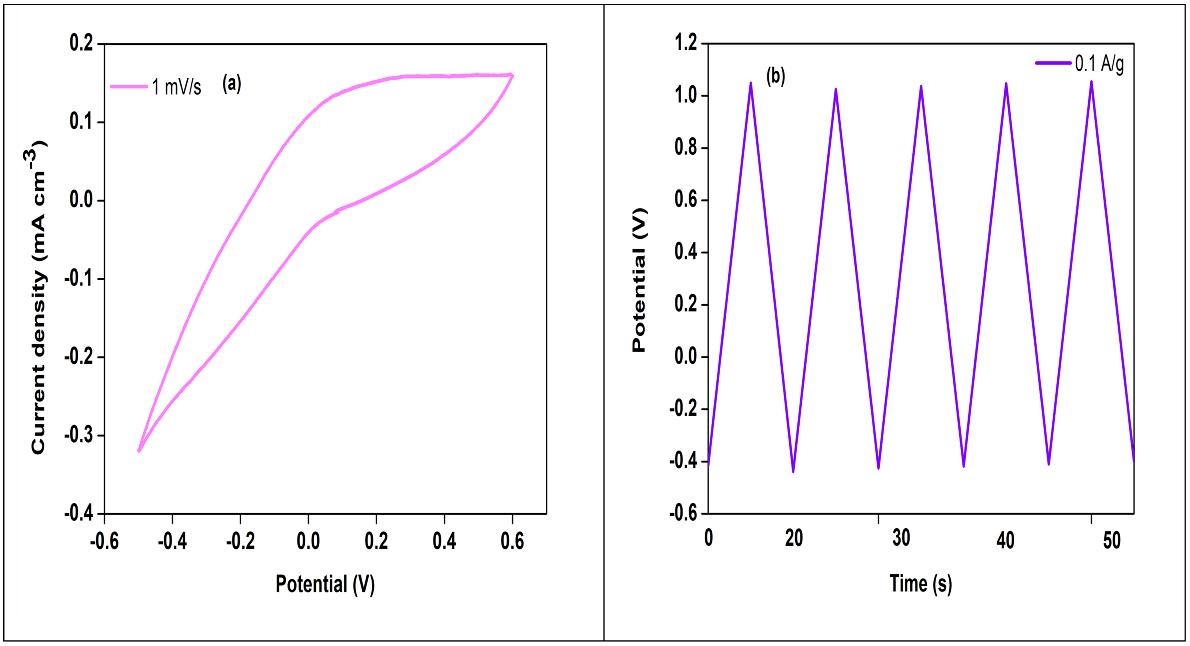

Fig 4. a) Cyclic voltametry of NPs with different scan rate in KCl solution. b) Charge discharge of NPs in KOH solution

4 Conclusions

This study introduces a green, cost-effective $MnMoO_4$ synthesis using *Salvia hispanica* fuel, yielding a highly conductive, low-resistance electrode with surface-controlled redox behavior and high capacitance. The material shows strong prospects for advanced supercapacitors, with future improvements recommended through composite formation, structural tuning, and extended electrochemical performance evaluation. The electrochemical characterization of the $MnMoO_4$ modified electrode revealed low solution and charge-transfer resistances (2.667 Ω and 1.628 Ω, respectively), indicating excellent electrical conductivity and efficient charge transport. Cyclic voltammetry results confirmed a surface-controlled redox process with well-defined anodic and cathodic peaks. The progressive increase in specific capacitance values 437.13 F·g^{-1} with the scan rate demonstrates enhanced electrochemical activity and superior capacitive behavior of the synthesized $MnMoO_4$ nanoparticles, suggesting their potential applicability in high-performance energy storage devices.

5 Author Contributions:

P.B.M..; methodology, P.B.M..; software, R.M. and S.G.; validation, S.I.A., S.G. and G.N.; formal analysis, S.I.A.; investigation, P.B.M and G.N.; resources, G.N. and D.K.P.; data curation, B.K.D.; R.M .; writing original draft preparation, S.I.A. and R.M .; writing review and editing, D.K.P.; D.R.B; S.G. and B.K.D.; visualization, G.N. and D.R.B.; supervision, P.B.M and G.N.; project administration, N.K.J.R and P.B.M. All authors have read and agreed to the published version of the manuscript.

6 Data Availability Statement:

All the raw data will be available upon reasonable request.

7 Conflicts of Interest:

The authors declare no conflict of interest.

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