TUNING OF REDOX ENERGIES BY SYNERGISTIC INTERACTION OF DIFFERENT TRANSITION METAL IONS FOR THE DEVELOPMENT OF HIGH-PERFORMANCE HYBRID SUPERCAPACITORS

Thesis submitted in partial fulfillment for the award of degree

Doctor of Philosophy

By

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Dedicated to my Beloved Family

CERTIFICATE

It is certified that the work contained in the thesis titled **"Tuning of redox energies by synergistic interaction of different transition metal ions for the development of high-performance Hybrid supercapacitors"** by ***"Abhay Narayan Singh"*** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy and SOTA for the award of Ph.D. degree.

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I, ***Abhay Narayan Singh***, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of **Dr. (Mrs.) Chandana Rath** and co-supervision of **Dr. Preetam Singh** for a period from **July 2017** to **July 2023** at the **Indian Institute of Technology (Banaras Hindu University)**, Varanasi, India. The matter embodied in this Ph.D. thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, thesis, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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Abbreviations

XRD	X-ray Diffraction
HR-SEM	High-Resolution Scanning Electron Microscope
HR-TEM	High-Resolution Transmission Electron Microscope
TGA	Thermogravimetric analysis
FTIR	Fourier transform Infrared Spectroscopy
XPS	X-ray Photoelectron Spectroscopy
BET	(Brunauer, Emmett, and Teller) specific surface
CV	Cyclic Voltammetry
ASCs	Asymmetric Supercapacitors
Cs	Specific capacitance
A, mA (unit)	Ampere, milliamp
AC	Activated Carbon
C, μC (unit)	Coulomb, microcoulomb
C	Capacitance
C^+/R^+	Cationic species in electrolyte
C^*	Complex differential capacitance
C^{+ve}	Capacitance of positive electrode
C^{-ve}	Capacitance of negative electrode
C_{Cell}	Overall cell capacitance
C_{Diff}	Capacitance from diffuse layer
C_{dl}	Capacitance from double layer
C_g	Gravimetric capacitance
C_H	Capacitance from Helmholtz plane
C_{IH}	Capacitance from inner Helmholtz plane
C_{OH}	Capacitance from outer Helmholtz plan
E°	Standard electrode potential
E_{Total}	Total energy stored in capacitor
EDLC	Electrochemical double layer capacitor

EIS	Electrochemical Impedance Spectroscopy
E_S	Electrochemical supercapacitor
f	Frequency
F	Faraday constant
F	Farad
g	Gram
I	Current
K (unit)	Temperature in Kelvin
k	Boltzmann's constant
M	Molar concentration
Q	Charge
V	Voltage
W(unit)	Watt
Wh (unit)	Watt hour
wt %	Weight percentage
ω	Angular frequency
Z^*	Total impedance
Z'	Real component of impedance
Z''	Imaginary component of impedance
EES	Electrochemical Energy Storage
LSV	Linear Sweep Voltammetry
GCD	Galvanostatic Charge-discharge
CA	Chronoamperometry