PREFACE

Two-dimensional (2D) nanomaterials have garnered significant attention in recent years due to their exotic properties and potential applications across various fields, including electronics, energy storage, biomedicine, and electrochemical sensing. 2D materials are a class of nanomaterials with one dimension confined in a nanoscale region (1-100 nm). This confinement endows th ese materials with ultrathin dimensions and a high surface-to-volume ratio. Furthermore, these 2D materials are often exfoliated from layered materials bound by van der Waals interaction. Due to removing these weak van der Waal interactions, these 2D materials exhibit remarkable mechanical strength and chemical properties that distinguish them from their bulk counterpart. The confinement of electrons in two dimensions significantly alters their electronic band structure, endowing them with unique electrical and optical properties.

The story of 2D nanomaterials began with the discovery of Graphene in 2004 when Geim and Novoselov exfoliated graphite using scotch tape and analyzed what was left on the tape. This discovery paved the way for the exploration of other 2D nanomaterials, such as transition metal dichalcogenides (TMDs), hexagonal boron nitride (hBN), metal oxides, and layered double hydroxides (LDHs). These materials' atomic-scale thickness and planar structure result in quantum confinement effects and surface phenomena that are not observed in three-dimensional materials. Consequently, 2D nanomaterials offer unique opportunities for innovations in nanoscale engineering and the development of next-generation technologies.

This thesis is centered around the use of 2D nanomaterials for application in diverse fields. Using the solvothermal method, I synthesized boron carbon nitride, an intermediate nanomaterial between graphene and hBN. The successful synthesis of this material is validated by extensive chemical and physical characterization. The synthesized material is used to modify the electrode surface, which is utilized as a sensing platform. I also investigated the use of hBN nanomaterial as anode material for sodium-ion batteries, following several computational studies claiming it as a potential candidate. hBN was also examined for modification of the separator used in sodium metal batteries to prevent dendrite growth. In another work, I fabricated a novel conductive hydrogel of BSA protein using graphene oxide and demonstrated its efficacy in accelerating wound healing. This thesis comprises seven chapters followed by references and a list of publications. A brief description of each chapter is given below.

Chapter 1 provides an introduction and overview of the 2D materials used in this thesis work. The unique properties of each material are discussed, various routes of synthesis are reviewed, and potential applications for these materials are examined. A discourse regarding the applications for which these materials are used is also provided. This section illustrates the potential societal benefits of these applications, includes a literature review, and identifies the knowledge gap that this research aims to fill. Finally, the scope of the thesis is discussed.

Chapter 2 discusses the instrumentation, materials, and methodology used for experiments. A detailed description of various instruments such as UV-Vis spectrophotometer, Fourier transform Infrared spectrometer, XRD, XPS, scanning electron microscope, and transmission electron microscope used for chemical and optical characterization of the materials is provided. Electrochemical techniques such as CV, DPV, and EIS are also discussed. This section also details the experimental protocols used for various nanomaterials' synthesis, characterization, and applications.

Chapter 3 describes the synthesis of BCN material using the one-pot solvothermal method and its application for the modification of screen-printed electrodes. Screen-printed electrodes (SPE) have emerged as reliable probes for portable, economical, and practical testing platforms in point-of-care applications. Compared to the conventional three-electrode systems, SPE requires significantly less sample volume and omits the cleaning and pre-treatment requirements. This work proposes a facile protocol for BCN-assisted SPE surface functionalization using cyclic voltammetry. The modified SPE showcased significantly improved electrochemical activity, with a 5-fold increase in current response and an 18mV potential shift. The fabricated sensing platform demonstrated high sensitivity and selectivity toward quantitative analysis of tryptophan with a detection limit of 36.4nM. Furthermore, the developed sensor was tested for monitoring TRP levels in complex matrices like food and human body fluids. This proposed approach to electrode modification holds promise for providing swift, precise, and cost-effective means for improving the sensitivity of SPE for trace level detections required for point-of-care applications.

Chapter 4 examines hexagonal boron nitride as an anode material for sodium-ion batteries (SIBs). We found several computational studies that examined the potential use of hBN as an anode for SIBs, but no experimental study validates these claims. To fill this knowledge gap, anode electrodes with two different morphologies of hBN were prepared, and their electrochemical performance was studied. Both morphologies showcased abysmal performance in hosting sodium ions with very low specific capacity. Although hBN nanoplatelets initially showcased greater capacity than bulk hBN, the specific capacity declined significantly in subsequent cycles, suggesting irreversible sodium adsorption on the more active sites available in nanoplatelet morphology. The obtained results provide experimental insight into the ineffectiveness of hBN in serving as SIB anode material, unlike the previous theoretical claims. We believe it is essential to report these discrepancies in the computational and experimental findings for the benefit of experimentalists working enthusiastically to explore and develop new anode materials related to boron nitride systems.

Chapter 5 investigates another application of hBN in sodium-based batteries for modification of separator material. This study aimed to prevent the growth of dendrites in sodium metal anodes, which is a significant challenge in the practical implementation of sodium-metal batteries. These dendrites reduce efficiency and battery lifetime and pose a severe danger of fire and thermal runaway by short-circuiting the battery by piercing through the separator. The morphology and thermal stability of bare and modified separators were investigated by scanning electron microscope and thermogravimetric analysis (TGA), respectively. The modified separator manifested improved thermal stability and stable electrochemical performance under limited sodium availability. The post-cycling SEM images of sodium anode exhibited significantly reduced dendrite growth in cells using a coated separator.

Chapter 6 presents the fabrication of a novel conductive hydrogel comprised of BSA protein and graphene oxide as an effective dressing for rapid diabetic wound healing. The mechanical and electrical properties of composite hydrogel were optimized by varying the concentration of graphene oxide. The prepared hydrogel exhibited superior antibacterial properties and enhanced biocompatibility compared to only BSA hydrogel. In-vivo studies conducted on the murine model showcased rapid wound healing in composite hydrogel-treated rats. This is attributed to hydrogel's ability to facilitate cellular activities through enhanced electrical conductivity by maintaining a continuous electrical signal at the wound site. The presented findings suggest that nanocomposite protein-based conductive hydrogel not only holds great potential for advanced diabetic wound care but also has potential for future innovation in tissue engineering, regenerative medicine, and beyond.

Chapter 7 concludes the outcome of the research work included in this thesis and briefly discusses the future of the scope of this work.