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Single-phase $BiVO_4$ decorated carbon composites derived from cashew nut shells as bifunctional materials for supercapacitor and photocatalytic applications

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Abstract

The rational design of bifunctional materials capable of treating environmental pollutants, such as toxic dyes, while also serving as efficient electrode materials for supercapacitor applications holds great potential for sustainable energy and environmental solutions. In this study, $BiVO_4$ with varying concentrations of Cashew nut shell-derived carbon composites was developed by a hydrothermal process and used effectively as an electrode and photocatalyst. The electrochemical analysis of $BiVO_4$/100 mg Cashew nut shell-derived carbon composite exhibits a higher specific capacitance of about 326 Fg^{-1}. The energy density and power density of the $BiVO_4$/100 mg Cashew nut shell-derived carbon composite were about 11.12 $Whkg^{-1}$ and 750 Wkg^{-1}, respectively. The fabricated electrode exhibited retention of about 87.19% after 5000 charge-discharge cycles. $BiVO_4$/100 mg Cashew C degraded the methylene blue dye entirely within 240 min. The proposed materials act as excellent photocatalysts and demonstrate their suitability for high-efficiency supercapacitor applications to meet future demands and needs.

Keywords

Asymmetric supercapacitor; $BiVO_4$; Cashew nut shell-derived carbon; Methylene blue

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Introduction

The evolution of technologies for energy harvesting, storage, and conversion has profoundly driven the advancement of human civilisation. However, this rapid technological progress has also contributed to severe environmental pollution, intensifying the global demand for clean and fresh water resources [1,2]. Various energy storage technologies, such as photovoltaic systems, biomass-based fuels, wind power, and fuel cells, have become increasingly significant in advanced technological industries. A key objective is to develop advanced energy storage devices that achieve compactness, reduced thickness, and enhanced portability for their integration into our daily lives [3,4]. Supercapacitors have considerable interest as efficient energy storage systems and

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power delivery solutions, owing to their outstanding attributes, including high power output, superior energy efficiency, and eco-friendliness [5]. Unlike traditional storage systems, supercapacitors feature a simplified charging process and do not suffer from memory-related limitations, contributing to improved safety. Furthermore, energy storage based on physical mechanisms offers greater stability and a longer operational lifespan than chemically driven storage technologies [6]. Supercapacitors are becoming more prominent in the field of electric transportation because of their rapid charging capability and strong potential to boost future transportation systems. Supercapacitors are classified by the principle of charge storage into EDLCs (Electric Double Layer Capacitors) and Pseudocapacitors (PCs) [7]. Mostly carbon-rich materials are utilized in EDLC-type supercapacitors, where they enable charge storage primarily through electrostatic interactions rather than redox reactions. On the other hand, transition metal oxides are recognised as a prominent category of pseudocapacitive materials on account of their multiple oxidation states, which promote rapid, reversible redox reactions. Despite offering higher specific capacitance than EDLCs, transition metal oxides often exhibit inadequate cycle stability and rate capability. As a result, there is a strong demand for materials that combine long-term stability with superior electrochemical performance [6]. Current research aims to develop highly efficient electrode materials by tuning the factors like the crystallinity, morphology, surface reactivity, capacitance and storage performance, which might improve the quality of the supercapacitor, that may maximise the potential window range of the energy storage devices [8,9].

The widespread destruction of ecosystems due to human activities has emerged as a critical global issue requiring immediate action. Although multiple factors contribute to ecosystem degradation, water contamination remains one of the most alarming environmental threats. A significant cause of this pollution is the discharge of untreated industrial waste into freshwater sources, which not only harms aquatic life but also increases the demand for clean water [10]. Organic dyes are the major components of industrial wastewater that contribute to pollution by the formation of harmful by-products as secondary pollutants through chemical reactions in the water. Organic dyes exhibit strong resistance to decomposition, remaining stable under both photochemical and physicochemical processes. Many processes, such as sedimentation, chemical precipitation, reverse osmosis,

ion exchange, adsorption, and biological membranes, are used for treating dye-contaminated water. Among various treatment methods, photocatalysis is recognised as a cost-effective and straightforward approach for purifying water contaminated with dyes and other pollutants [11,12]. Over the past decade, extensive research has been concentrated on exploring photocatalytic technologies and their environmentally friendly applications. Furthermore, photocatalysis offers an additional advantage by preventing the formation of secondary pollutants during treatment [13]. Addressing energy and environmental challenges has driven the development of multifunctional materials with enhanced properties.

Exploring novel types of pseudocapacitive electrode materials remains crucial for boosting the performance of supercapacitors [14]. In recent times, bimetallic transition-metal oxides such as Bi_2MoO_6, [15] $ZnCo_2O_4$, [16] $NiMoO_4$ [17,18], and $NiCo_2S_4$ have emerged as desirable candidates for electrodes in efficient energy storage devices [19]. Additionally, vanadium-based oxides are economically viable materials that exhibit multiple oxidation states (3+ to 5+), excellent electrical conductivity, and high specific capacitance, making them well-suited for use as electrode materials [20]. Bismuth vanadates, featuring an optical band gap of approximately around 2.4–2.5 eV, demonstrate remarkable light absorption capability, notable resistance to chemical degradation, and enhanced electron transfer potential, while also being non-toxic [21]. These attributes make $BiVO_4$ suitable for use as a dye as well as a highly efficient material in photocatalytic and photoelectrode-based applications [22,23]. $BiVO_4$ nanoparticles can exist in three structural phases: tetragonal zircon-type (tz-$BiVO_4$), tetragonal scheelite-type (ts-$BiVO_4$), and monoclinic scheelite-type (ms-$BiVO_4$), depending on the factors associated with crystallographic lattice configuration [8]. Despite its excellent physicochemical properties and stability that make $BiVO_4$ a potential material for energy storage applications, its inherently low electrical conductivity remains a drawback, limiting its ability to maintain capacitance and perform efficiently during high-speed charge–discharge cycles [8,24]. To overcome this limitation, carbon-based hybrid composite materials can be employed to enhance the specific capacitance and overall electrochemical behaviour of the material. Various carbonaceous materials, such as graphene, carbon fibres, and nanotubes, have been explored for supercapacitor applications, but their synthesis often requires complex procedures and is expensive. To make production more

affordable, activated carbons derived from biomass with distinctive structures are a promising low-cost alternative, using sources such as rice husks [25], loofah [26], waste coffee, peanut shells [27], pumpkin seeds, bamboo etc. [28] Among the various synthesis methods, the hydrothermal approach, a typical soft-chemical technique, offers distinct advantages in producing highly crystalline and pure materials. Refining the reaction parameters allows well defined controlled over the morphology and crystalline nature of the materials [[29], [30], [31]].

While both $BiVO_4$ and biomass-derived carbon materials have been individually investigated in previous studies, the novelty of the present work lies in the development of a sustainable $BiVO_4$/cashew nut shell carbon composite with an optimized composition that simultaneously enhances photocatalytic and electrochemical performances. The present work reports the hydrothermal synthesis of $BiVO_4$ with carbon composites derived from cashew nut shells at varying concentrations. The structure, phase formation, and morphology of the synthesised materials were analysed using basic characterisation techniques, including XRD, Raman, and SEM. The materials were employed as electrodes for supercapacitor applications and as catalysts for dye degradation. The cashew nut shell carbon, or cashew carbon (CC), has been incorporated, and its influence on enhancing the electrochemical behaviour of the bismuth vanadate particles was studied through various electroanalytical investigations, including CV, GCD, and EIS. The asymmetric supercapacitor electrode was further fabricated to examine the practical potential of the material. Fig. 1 depicts the schematics of the synthesised $BiVO_4$ and its carbon-based composites employed for energy and environmental applications.

Section snippets

Materials

Bismuth (III) nitrate pentahydrate ($Bi(NO_3)_3 \cdot 5H_2O$) and Vanadyl Acetyl Acetonate ($C_{10}H_{14}O_5V$) were purchased from Merck Life Sciences. Glacial Acetic Acid (CH_3COOH) was purchased from Nice Chemicals, oleic acid ($C_{18}H_{34}O_2$) and methyl alcohol (CH_3OH) were purchased from SISCO laboratory. All the precursors were used without any further purification. …

Preparation of biocarbon from cashew nut shell residue

Cashew nut shell carbon (CNSC) was produced using 100 g of cashew shell leftovers. After being washed with deionised water to remove surface residues, …

XRD analysis

The structural purity and crystalline nature of the as-prepared Pure $BiVO_4$, $BiVO_4$/40 mg Cashew C, $BiVO_4$/60 mg Cashew C and $BiVO_4$/100 mg Cashew C electrode material were investigated using XRD. The XRD profiles of BiVO4 and its composite material are shown in Fig. 2, with 2θ ranging from 5 to 90°. The resulting diffraction pattern correlates well with standard data (JCPDS Card No: 01-075-2480), whereas the synthesised BiVO4 nanoparticles exhibit a monoclinic crystal structure with the space …

Conclusions

In summary, $BiVO_4$ composites incorporating varying amounts of cashew nut shell-derived carbon were synthesised via a hydrothermal route in the presence of oleic acid, and their structures and formation were studied using XRD. Raman and XPS studies examined the vibrational properties and elemental composition of the material, respectively. At the same time, the SEM revealed the smooth, sphere-like morphology of the synthesised nanocomposites. Electrochemical studies demonstrated that the $BiVO_4$ …

CRediT authorship contribution statement

Bagavathy Shunmughananthan: Formal analysis, Methodology, Writing – original draft. **Linghesh Subramani:** Writing – original draft. **Sivakumar Ramamurthy:** Writing – review & editing. **Senthil Kumar Krishnamoorthy:** Writing – review & editing. **Ramesh Rajendran:** Formal analysis, Writing – review & editing. **Balaji Krishnasamy:** Writing – review & editing. **Thangaraju Dheivasigamani:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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