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Molybdenum disulfide and its composites for Supercapacitor application: A Review

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Abstract

A transition metal dichalcogenide, molybdenum disulphide (MoS_2) possesses unique properties, including a configurable bandgap, and a broad spectrum of potential applications in catalysis, electronics, and energy storage. It proved to be an effective electrode material for supercapacitors due to its high specific capacitance. Here electrochemical performances of MoS_2 and its composites with different preparative methods and conditions have been summarized. The main advantages and disadvantages of MoS_2-based electrodes are also covered in the review.

Keywords; Electrochemical performance, Molybdenum disulphide, Specific capacitance Supercapacitor.

INTRODUCTION

Every activity of our day to day life requires energy which put big pressure on our conventional energy sources. It is imperative to establish a consistent source of pure energy due to the escalating global energy demand, which has resulted in the emergence of new ecological issues. However, effective and economical energy storage technologies are required for this consistent clean energy. The society benefits greatly from an energy storage system that is friendly. To improve energy storage, new materials must be developed and used at the core of energy-storage systems [1-3]. In recent years, researchers have been concentrating on the creation of "novel materials for energy storage devices like supercapacitors".

Supercapacitors, often referred to as electrochemical capacitors or ultracapacitors, are devices that store energy that are intended to fill the gap among batteries and capacitors by providing quick charging capabilities to satisfy intermediate-specific energy needs [4-8]. The technology of supercapacitors has been in existence for more than fifty years and is widely regarded as one of the most promising energy storage systems. Their energy density is approximately 5Wh/kg, which is lower than that of batteries. However, they offer numerous advantages, including a rapid charge-discharge rate, high power, extended lifespan, and environmentally friendly operations [9-12]. To address the issue and satisfy the needs of upcoming systems such industrial appliances, hybrid electrical cars, and portable gadgets, the development of novel materials is the primary method used to enhance supercapacitors. Energy storage has made extensive use of carbon-based materials including graphene, carbon nanotubes, carbon aerogel, and activated carbon, as well as transition metal chalcogenides like MoS_2, WS_2, and VS_2 [13]. Because of their remarkable electrical conductivity, inherent flexibility, and low weight, activated carbon and graphene are the most studied "electrode materials for energy storage devices" [14-15].

Researchers have demonstrated an interest in “the two-dimensional nanostructure of molybdenum disulphide (MoS_2)”, which is one of the numerous transition metal-based active materials.

As with graphite, it is characterised by a layered structure with feeble "van der Waals contacts between S-Mo-S layers". Compared to graphite, which has a gap of 0.335 nm between layers, this material has a distance of 0.615 nm [16]. It demonstrates favourable capacitive properties as a result of its sheet-like morphology and substantial surface area [17- 18]. Realising the full benefits of 2D MoS_2 requires a three-dimensional architecture made of pure 2D-MoS_2, which has shown excellent durability in preserving "the individual nanosheet" with a fully exposed surface area [19-20]. Both MoS_2's specific capacitance and electrical conductivity remain below those of carbon materials such as graphene, making it unsuitable for energy storage applications. Many researchers have created a variety of MoS_2- and graphene-based nanocomposites to address these shortcomings and achieve favourable electrochemical properties. In comparison to pure MoS_2, the MoS_2-based composites exhibit exceptional cyclic stability and a high specific capacity, as evidenced by the electrochemical experiments [21-30].

In this section, we present a comprehensive summary of the most recent advancements in "MoS_2 and MoS_2-based composites", in addition to their application in supercapacitors. The final perspective is a discussion of the future opportunities and remaining significant challenges for MoS_2 material.

MATERIAL AND METHODS FOR MoS_2 PREPARATIONS AND ITS APPLICATION IN SUPERCAPACITOR

Electrochemical performance of MoS_2 and its Composites

The procedure and the preparative parameters have a significant impact on the supercapacitor's performance because they alter its structure and shape [31-32]. The electrode materials graphene and molybdenum disulphide (MoS_2) have been used in a number of energy-related applications. Exploiting MoS_2's electrochemical performance has been the focus of several research groups. A well aligned multiwalled carbon nanotubes sheet of MoS_2-Graphene fibers by incorporating MoS_2 and grapheme nanosheet followed by twisting was fabricated by Sun et al [22]. High columbic efficiency, strong cycle stability, and enhanced energy density were all possible with this fiber-based asymmetric supcapacitor operating in “the broad potential window of 1.4 V”. According to Patil et al., a variety of carbon materials, including "graphene, carbon nanotubes (CNT), and activated carbon (AC)", have been used extensively as electrode materials in supercapacitors because to their excellent cyclic stability, high electrical conductivity, and straightforward surface functioning. When created by electrophoretic deposition, the MoS_2/GO hybrid electrode retains "a high specific capacitance of almost 613 F g−1" at a low scan rate, based on electrochemical supercapacitive tests [25]. A MoS_2 thin film was created by Pujari et al. [33] using a soft chemical synthesis technique at low temperatures. At a power density of 2.1kW/kg, the MoS_2 thin film exhibited "a gravimetric energy density of 23 W h/kg and a specific capacitance of 180 F/g at 5 mv/s". Masikhwa et al.'s composite showed outstanding cyclic stability, holding onto 95% of its capacitance after "2000 cycles with a maximum capacitance of 59 F/g at a current density of 1 A/g" [34]. Because of its interesting features and possible uses, graphene is the 2D layered substance that has been studied the most. For supercapacitor electrode applications, its excellent electrical conductivity, flexibility, and huge surface area make it the perfect material [35-38]. The class of materials known as graphene is suited for the growth of other materials due to its distinct planar structure. The development of MoS_2 nanosheets on graphene's layers may reduce the possibility of individual nanosheets self-aggregating since graphene may act as a conducting network. "The MoS_2-Graphene composite coin self supercapacitor" was reported by Bisset et al. with a scan rate of 5 mV/s, with a precycling capacitance of 4.29 mF/cm [39]. After 10,000 cycles, the membrane electrode's postcycling capacitance, or capacitance enhanced by 250%, was 11 mF/cm^2. A hybrid supercapacitor was developed by Zhan et al. by fabricating Li-HSc and Na-HSc and utilising "a 3D interlayer expanded MoS_2-Graphene in an organic electrolyte of $LiPF_6$ and $NaClO_4$" [40]. A binder-free supercapacitor electrode was reported by Yin and colleagues, who used commercial carbon fibre to create MoS_2 nanosheets [41]. Using readily detachable gibbsite nanoplatelets, Quan et al. created “hollow Carbon-MoS_2-Carbon hybrid nanoplates” [42]. This carbon-MoS_2-carbon symmetric supercapacitor demonstrated "a high specific capacitance of 248 F/g at 0.1 A/g". Graciadali and colleagues developed asymmetric supercapacitors by combining single-walled CNT with cathodically exfoliated MoS_2 nanosheets [43]. "A high energy density of 26 Wh/kg" was achieved by this supercapacitor when the power supply rate was 1.5V. MoS_2/CNT/Graphene nanoflakes' electrochemical effectiveness was reported by Ali and associates [44]. MoS_2 thin film homogenous ultrathin nanoflakes have been successfully created using the simple

and affordable room temperature Chemical Bath Deposition (CBD) procedure. These nanoflakes are then used as supercapacitor electrode material [45].

Nancomposites of MoS_2 include MoS_2 /CNT, MoS_2 /Carbon aerogel, MoS_2 /Graphene, MoS_2 /Polymer, MoS_2 /carbon derivative/Polymer composites. These materials' high electrical conductivity, huge surface area, and regulated surface functionality make them a good choice for supercapacitor applications. The electrochemical performance of the MoS_2 carbon composites that were tested is illustrated in Table 1. Because of its physical and chemical properties, graphene has attracted a lot of attention, much like other carbon compounds. It has strong heat tolerance, conductivity, and a large and considerable surface area. In addition to its strong mechanical strength, it has been shown that MoS_2 and graphene harmonise to correct material imperfections, advance electrochemical performance, increase conductivity, provide more active sites, and speed up electron transfer and electrolyte diffusion in electrode material [46-49].

Table 1 Electrochemical supercapacitor performance of MoS_2 /Carbon composite electrodes.

Material structure	Electrolyte	Specific capacitance F/g	Current density A/g	Number of cycles	Specific capacitance obtained %	Energy density (Wh /kg)/ Power density (kW/kg)
MoS_2/ Graphene	1M Na_2SO_4	243	1	1000	92.3	73.5/19.8
MoS_2/ CNT	1M Na_2SO_4	108	0.1	-	-	7.4/3.7
MoS_2/ carbon aerogel	1M Na_2SO_4	260	1	1500	92.4	-
MoS_2/3D graphene network	3M KOH	1972.58	1	4000	110.57	-
MoS_2/ Graphene wrapped CNT	-	498	1	10,000	94.3	-
Carbon/Mo S_2 nano-sphere			20		93	-

The electrochemical efficacy of MoS_2/Graphene is influenced by three principal variables: MoS_2 structural constantancy, C-O-Mo interfacial contact, and "MoS_2 to graphene electron transport" combine to provide an amazing and reversible capacity [50-53]. Because the hybrid graphene gives the MoS_2 mounting a lot of surface area, the electrode structure is uniform, and the MoS_2 frame is modified as the cycle progresses. In the MoS_2/Graphene hybrids, internal conductive channels and apertures provide a significant number of active sites and enhance surface area. This improves electrode reaction kinetics and electrolytic performance by providing a continuous channel for ion intercalation and electrochemical reaction.

According to Rajapriya et al [54] the MoS_2 microflower electro spunned over carbon nanofiber forms 3D structure and shows robust charge transfer. Another problem is the significant shift in MoS_2 volume and the decreased electrical conductivity. Zheng et al.'s [55] active encapsulation method produced core shell MoS_2/Mesoporous Hollow Carbon Sphere (MHCS) nanocomposits, which demonstrated large surface area, high capacitance of 610F/g at 1A, and outstanding cycle performance. The MoS_2 nanosheet within the MoS_2/hollow carbon nanobowl demonstrated exceptional volumetric and "gravimetric capacitance of 560 F/g at 0.2 A/g" and enhanced gravity and volumetric capacitance [56].

Synthesis of MoS_2: Top-down approach and Bottom-up approach

There are two ways to synthesise MoS_2 nanoparticles, which directly alter the characteristics of the electrode material. The bottom-up strategy makes use of wet chemical synthesis methods such chemical bath deposition and hydrothermal synthesis, whereas the top-down strategy employs chemical and mechanical exfoliations.

In order to create high-quality films on a wide scale, the bottom-up method, which is economical and has a quicker development rate, combines hydrothermal, chemical vapour deposition, and chemical bath deposition. The method is lagging to produce single layer material which could be treated as the drawback.

Top-down approach is process of material formation. It includes the method like sputtering, vacuum evaporation, chemical exfoliation and Ball milling have high yield and used for large scale synthesis and produce the particles with high surface area. It requires inert condition and toxic solvents which may be the shortcomings of the methods. The various techniques and “supercapacitance of MoS_2/Carbon composite electrodes” in various electrolytes are shown in Table 2.

Table 2 Synthesis methods and corresponding supercapacitance of MoS_2/Carbon composite electrodes in different electrolytes.

Synthesis method	Electrolyte	Specific Capacitance	Energy and power density	Cyclic stability	Remarkable thing
Liquid phase exfoliation	1 M KCl	148 F/g at 1 mV/s	---	94% over 1000 cycles	Excellent cyclic stability
Liquid phase exfoliation	0.1 M KCl	40 F/g at 0.5 A/g	---		Exfoliation using three different Organolithium compounds
Hydrothermal	3 M KOH	1531.2 F/g at 5 mA/cm^2	34 wh/kg & 333.3W/kg	81.6% over 3000 cycles	High specific capacitance
Hydrothermal	1M Na_2SO_4	151.1 F/g at 10mA/cm^2	11/13 Wh/kg & 250 w/kg	90.6% over 2000 cycles	Flexible electrode over carbon cloth
Microwave assisted hydrothermal	1 M KCl	248 F/g at 5 mV/s		96% over 1000 cycles	MoS_2 grown on carbon nanofibres
Hydrothermal	1 M KCl	403 F/g at 1 mV/s		80% over 2000 cycles	Mesoporous nanostructure

Chemical Exfoliation

This method uses liquid exfoliation or mechanical cleavage to exfoliate bulk MoS_2 into thin layers. By using the ion intercalation approach to exfoliate MoS_2, large-scale production may be accomplished. Restacked MoS_2 sheets are prepared by a two-step process called ion intercalation. Small ions, such lithium (Li), are inserted into the MoS_2 layers in the first stage, while a reaction between water and intercalation occurs in the second. Hydrogen gas is created when the ion and water react. Solvents such as isopropyl alcohol, ethanol, and methanol may be implemented to optimise results.

High-quality, single-layer MoS_2 sheets are produced in huge quantities via liquid phase exfoliation. Thin MoS_2 sheets were created by Chen et al. [57] using an organo-lithium aided exfoliation process. To create thin 2H-MoS_2 sheets, bulk MoS_2 was exfoliated "using imidazole organic salt". The formation of 2H-MoS_2 films was verified by XPS analysis. "A volumetric capacitance of 410 Fcm^{-3}" was achieved by the development of a composite paper supercapacitor composed of MoS_2 and carbon nanotubes. In order to generate 1T MoS_2 nanosheets, bulk MoS_2 intercalated with organo-lithium was exfoliated by immersing it in water. Volumetric capacitances of 560 and 250 Fcm^{-3} were provided by the coin cell graphene composite supercapacitor in "an aqueous and non-aqueous electrolyte, respectively". After 5000 cycles, more than 90% of the capacity was retained [58]. Lithium intercalation and exfoliation method was used by Sarode and Patil [59]. They used a stainless steel collector to create MoS_2 nanosheets. According to FESEM research, closely packed inerratic nanosheets changed into highly dispersed nanoflakes during lithium exfoliation. Cyclic voltammetry yielded a specific capacitance value of 148 F/g at a scan rate of 1 mV/s. At a current density of 0.1 mA/cm^2, 2D MoS_2 nanosheets that have been exfoliated in the liquid phase with ethylenediamine (EDA) exhibit "a specific capacitance of 1348 mF/g". A high-yield technique that generates nanosheets with a lateral dimension of up to two micrometres is liquid phase exfoliation that is facilitated by EDA [60]. Ambrosi et al. [61] exfoliated MoS_2 using three different organolithium compounds: n-butyllithium (n-Bu-Li), tert-butyllithium (t-Bu-Li), and methyl-lithium (Me-Li). The degree of exfoliation varied depending on the organolithium compound. The increased surface area of "the n-Bu-Li and t-Bu-Li exfoliated MoS_2" resulted in better capacitance. MoS_2 quantum sheets were made by Nardekar et al. [62] using a ball milling technique with salt assistance. The MoS_2 quantum sheet's specific capacitance was higher than the bulk MoS_2's. The overall capacitance of MoS_2 was also influenced by the quantum capacitance. This capacitance was caused by the phase change of the two unpaired electrons "from the 2H to the 1t phase". It showed an 84% cyclic stability over 5000 cycles, "a specific capacitance of 160 F/g at a constant 1 mA current", and an energy density of 14.46 Wh/kg at a power density of 200 W/Kg.

The Environmental Approach (Green synthesis)

Wang et al. have created an environmentally friendly, cost-effective, and high-performing supercapacitor electrode

[63]. It comprises MoS_2/graphene ink and few layers of MoS_2.This 2D sandwiched supercapacitor displayed specific capacitance above 390 F/g at 5mV/s. Zhao et al. [64] used an environmentally friendly method and were successful in creating MoS_2/Carbon utilising “cornstalks as a bio-carbon source”. Their huge surface area demonstrated a capacitance of around 0.340 microfarad/g and high stability as an anode in a supercapacitor. Carbon from corncobs is used to create MoS_2/activated carbon (AC). Sangeetha and Selvakumar developed nano-flower like MoS_2 on the nano flakes biomass. In comparison to activated carbon and MoS_2, the combination demonstrated “a specific capacitance of 0.333 µF/g, a current density of 0.001 µA/g, and a capacitance retention loss of 20% after 7000 cycles". These values are 16 and 4 times higher, respectively. [65] used waste management strategies and the maximum amount of accessible sources. First, they obtained activated carbon from biomass tendu leaves. Supercapacitors made of the synthesised MoS_2/activated carbon were used. Its specific capacitance was 0.193 µF/g, and its specific surface area was 1509 m^2/g. The activated carbon showed both micropore and mesopore structure. A container made of polyethylene terephthalate served as a second supply of activated carbon, with 900 m^2/g of surface area. Sangeetha et al. found that a sponge-like network of activated carbon with a little MoS_2-carbon layer has a power density of 469W/kg [66].

Hydrothermal Method

Using bottom-up approaches, such as the hydrothermal process, 2D nanoparticles may achieve high surface area and excellent crystallinity. This is the most popular and extensively used method for creating metal sulphide nanoparticles. This method uses ultrasonic dispersion or magnetic stirring to dissolve precursors in deionised water. Addition of acid or base to the precursor solution results in the adjustment of the necessary acidic or basic pH value. The reaction is then completed by placing the solution in "a stainless steel autoclave and keeping" it there for a predetermined period of time at a high temperature [67]. This process is the best way to create nanostructures with great crystallanity and purity. The hydrothermal approach with surfactant support was used by Bai et al. [68] to synthesise MoS_2 nanosheets. MoS_2's specific capacitance is enhanced by sodium dodecylbenzene sulphonate, an anionic surfactant. Increased capacitive characteristics are the result of a few layer structure and rapid electron transit. The supercapacitive efficacy of the binder-free MoS_2 nanosheets was assessed in both acqueous and organic electrolytes using plasma-pyrolized cellulose microfiber. The cutoff frequency in an aqueous electrolyte capacitor was “103 Hz at a phase angle of -45 degrees” [69]. For nano MoS_2 nano sheets, Nagarjuna et al. used the hydrothermal method to get "a higher specific capacitance of 1531 f/g at 5 mA/cm^2" [70]. MoS_2 nanosheets exhibit double layer capacitance behaviour when produced on “carbon cloth (CC) at varying temperatures”. The greatest areal capacitance of the MoS_2/CC electrode at 200 degrees Celsius was "2236.6 mF/cm^2 at a current density of 10 mA/cm^2" [71]. $Na_2MoO_4.2H_2O$ and $(NH_2)_2CS$ were used as precursors by Wang et al. [72] to produce a titanium plate MoS_2 electrode devoid of binder. A specific capacitance of 133 F/g was demonstrated by "the MoS_2 nanosheet array on the Ti plate" at a current density of 1 A/g. Exceptional capacity retention was demonstrated by the electrode at energy density of 11.11 Wh/kg and power density of 0.53 kW/kg.

Sari and Ting [73] used a hydrothermal process aided by a microwave to "synthesise MoS_2 nanowalls on carbon nanofibers". At a scan rate of 5 mV/s, the electrode's specific capacitance of 248 F/g "and its 96% capacitance retention after 1000 cycles demonstrated" its exceptional electro-chemical performance. Thioacetamade and sodium molybdate were used as precursors to create mesoporous MoS_2 nanostructures. "Cyclic voltammetry tests of the Na_2SO_4 and KCL electrolytes" at a scan rate of 1 mV/s revealed specific capacitance values of 376 F/g and 403 F/g, respectively. "After 2000 cycles, the MoS_2 nanostructure electrode" exhibited an exceptional cyclic stability of around 80% [74]. The truncated nanograin-like MoS_2 nanostructure, which was generated at an acidic pH, exhibited “a specific capacitance of 190 F/g when the scan rate was 20 mV/s” [75]. To create the MoS_2 sponge electrode, Balsingham et al. used a straightforward hydrothermal process and freeze drying [76]. 510 F/g was the specific capacitance measured at a scan rate of 2 mV/s. It was reported that at a power density of 50 w/kg, "the energy density was 6.15 w/kg". After 4000 cycles, this supercapacitor retains more than 80% of its capacitance. At a current density of 1A/g, the ammonium-assisted hydrothermal method produced "swollen ammoniated MoS_2 with 1T/2H hybrid phases", which demonstrated cyclic stability of 95.4% after 2000 cycles and a specific capacitance of 346 F/g [77]. 3D flower-like MoS_2 microspheres were synthesised using a hydrothermal method aided by zinc ions [78]. A hierarchical MoS_2 microsphere is formed by the MoS_2/ZnS composite. "At a current density of 3 mA/cm^2, binder-free MoS_2 nanosheets grown on carbon textiles maintain" a capacitance of 103.5 mF/cm^2 after 15,000 cycles [79]. Wang et al. [80] used a hydrothermal technique to create MoS_2 nanospheres

using $MnCO_3$. MoS_2 nanosheet development on the MnS surface is indicated by surface morphology. Higher suitability for supercapacitor applications was shown by this material's 92.9% cyclic stability over 1000 cycles and 142 F/g specific capacitance at 0.59 A/g current density. "Using a one-pot hydrothermal process, Krishnamoorthy et al. [81] generated a MoS_2 electrode on Mo foil without the use of an adhesive."A specific capacitance of 192.7 F/g" was demonstrated by the MoS_2/Mo binder-free electrode in charge discharge studies with a current density of 1 mA/cm^2. The double layer capacitance and pseudo capacitance are added together to get the total capacitance. After 1000 CV cycles at a scan rate of 50 mV/s, the electrode demonstrated high columbic efficiency of 98.5% and 98% cyclic stability at "a current density of 2 mA/cm^2". Using MoS_2 supercapacitors, Kesavan et al. investigated their heat dependence [82]. The hydrothermal approach of producing MoS_2 nanosheets using thiourea and MoO_3 powder as precursors is more successful at "temperatures between 20 and 80 degrees Celsius". At a scan rate of 5 mV/s, the specific capacitance rose from 35.46 to 44.94 F/g between 20 and 80 °C.

Other Chemical and Physical Methods.

Numerous techniques for creating MoS_2 electrodes have been documented. MoS_2 nanoparticles may be easily deposited via chemical bath deposition. It is low cost, trouble free method and film can be controlled by controlling operating parameters. Single step chemical approach can be used to deposit binder free nanograins on "stainless steel substrate". The specific capacitance of "the amorphous MoS_2 nanostructure was 180 f/g" at a scan rate of 5 mV/s [83]. MoS_2 nanoflakes were applied to a stainless steel substrate by Karade et al. [84]. From 0.1 to 0.5 M, the capacitance was investigated for various Na_2SO_4 concentrations. At a scan rate of 5 mV/s, the electrode was measured to have "a maximal specific capacitance of 576 F/g in 0.5M electrolyte and an energy density of 14.58 Wh/kg". "Multiwalled carbon nanotubes (MWCNT)" were coated on MoS_2 nanoflakes in the aforementioned procedure to study a small increase in supercapacitive performance. The specific capacitance of the electrode was 591 F/g when "it was scanned at a rate of 5 mV/s" [85].

Choudhari et al. [86] deposited a thin layer of MoS_2 on copper foil using radio frequency magnetron sputtering. CV and GCD examined the electrochemical performance at a range of current densities and scan speeds. The material's ELDC behaviour was suggested by the CV curves' elliptical shape. For varying thicknesses, the thickness-dependent performance was also assessed. Specific capacitance was 27.82 mF/cm^2 for the 250 nm-thick film and 33 mF/cm^2 for the 1 micron-thick film. At a power density of 80 W/cm^3, the electrode showed "a high energy density of 1.622-2.33 mWh/cm^3" and a high cyclic stability of 97% after 5000 cycles. MoS_2 nanoworms were generated on copper foil by Neetika et al. through the utilisation of "the DC magnetron sputtering method" [87]. The electrochemical performance was determined to be exceptionally exceptional, with a specific capacitance of 138 F/g, a current density of 1A/g, "an 86% retention of capacitance over 5000 cycles, an energy density of 12.26 Wh/kg, and a power density of 0.4 kW/kg".

In order to create nanowalls, Mei Soon and Loh [88] used the chemical vapour deposition approach. A 1.4 micrometre thick film showed better capacitance than a thinner one because the densely packed nanowalls of thin films affect "the migration of electrolyte ions into the electrode". Pazhamalai et al. [89] employed thermal breakdown to convert a $(NH_4)_2MoS_2$ source into crystalline MoS_2. Testing was conducted on the symmetric supercapacitor that was constructed "using a 0.5 M $TEABF_4$ organic electrolyte". During a 5mV/s scan, the device exhibited "a specific capacitance of 39.93 F/g and an energy density of 20.68 Wh/kg".

Compared to materials based on carbon, "the MoS_2 electrode has a higher resistance". "A composite of MoS_2 and carbon" derivatives was created in order to get around this problem. When MoS_2 nanoflower was cultivated using "Wang et al.'s one-step hydrothermal technique" on corncomb-derived activated carbon (CB-C), the surface area rose [90]. The MoS_2/CB-C electrode's CV curves' rectangular form validated the EDL behaviour. An energy density of 7.6 Wh/kg, a power density of 608 W/kg, and "a specific capacitance of 38.3 F/g" were shown by the symmetric supercapacitor created with this method at a current density of 1 A/g.

Sing et al. [91] used a straightforward hydrothermal technique to produce MoS_2 that resembled flowers. In addition to designing a solid-state supercapacitor, "a MoS_2 hybrid and 3D graphene" were created on graphite. With an energy density of 4.59 Wh/kg and a power density of 8.8 W/kg, this supercapacitor had a specific capacitance of 58 F/g. A 9 V battery can only charge an LED for 25 seconds when these four supercapacitors are connected in series. This allows the LED to be lighted for 40 seconds.

Utilising MoS_2 graphene nanocomposite, Bissett et al. have developed a supercapacitor that is shaped like a coin [92]. Using the liquid phase exfoliation technique, MoS_2

nanoflakes were produced. At a 5 mV/s scan rate, the electrode's specific capacitance was 11 mF/cm^2. The L-cysteine assisted solution phase approach was used by Huang et al [93]. The 3D sphere-like graphene composite showed "a specific capacitance of 243 F/g and 92.3% capacity retention after 1000 cycles at a current density of 1 A/g". To fabricate "the MoS_2/reduced graphene oxide (rGO) electrode", a MoS_2-graphene dispersion drop cast was employed over a Ti lattice. Cyclic voltammetry was conducted for a variety of MoS_2/rGO ratios, including 10:1, 5:1, and 2:5:1. "A specific capacitance of 176 mF/cm^2" was measured for a 5:1 MoS_2/rGO electrode at a scan rate of 10 mV/s [94].

The MoS_2/rGO/MoS_2 nanocomposite was synthesised on Mo net by Zhang et al. [95] using an in situ hydrothermal method. It appeared under a FESEM as a cabbage-like form with a wrinkled surface. The specific capacitance of the electrode was 455.3 F/g when the current density was 20 mA/cm^2. This method produces a supercapacitor with a high cyclic stability, "maintaining 89.8% of its capacitance after 4000 cycles". It has a power density of 1.87 kW/kg and an energy density of 6.22 Wh/kg. Using the dipping and drying method, Zhou et al. [96] grew MoS_2 nanosheets on top of a three-dimensional graphene network. There was a big difference between "the specific capacitance of the low-content MoS_2 sample" and the medium-content MoS_2 sample that was dipped and dried three times. A power density of 400 W/kg and an energy density of 36.43 Wh/kg were produced by this coin-shaped supercapacitor device. On 3D Ni foam, a MoS_2/rGO electrode was created using two sequential layers. The capacitance was 60% higher with the SILAR approach "(1071 F/g at 2 A/g current density) than it was with pure MoS_2 (661 F/g at 2 A/g)". At a power density of 7.4 kW/kg, an asymmetric supercapacitor device utilising MoS_2/rGO as the positive electrode and rGO as the negative electrode demonstrated "a 92% capacitance retention over 4000 cycles and an energy density of 72.8 Wh/kg" [97].

"The specific surface area and electrical conductivity" of the MoS_2 electrode were increased by Fan et al. [98] through the incorporation of carbon into MoS_2 nanosheets. The greatest specific capacitance of these flowers, such as the MoS_2/carbon electrode, is "201.4 F/g at a current density of 0.2 A/g". "A hybrid co-synthesised aerogel rGO-MoS_2-Co" was created by Gigot et al. [99] by hydrothermally combining a few layers of rGO with sheets of molybdenum disulphide. "A specific capacitance of 416 F/g" was found by the GCD measurement at a current density of 1 A/g. According to Naz et al. [100], increased defect density results in higher specific capacitance because of enhanced charge transfer routes and more active sites. After 3000 cycles, the cyclic stability was 84.5%, and "the specific capacitance was 442 F/g at a current density of 1 A/g". Firmiano and colleagues [101] conducted a comparative electrochemical analysis of MoS_2 layer concentrations on graphene at "low (LCMoS_2/rGO), medium (MC MoS_2/rGO), and high (HCMoS_2/rGO) levels". "The specific capacitance values of the MoS_2/rGO electrodes" were 128, 265, and 148 F/g, as determined by CV testing, when the concentrations were low, medium, and high. Compared to MCMoS_2/rGO and HCMoS_2/rGO electrodes, LCMoS_2/rGO demonstrated remarkable cyclic stability, "which included a 92% capacitance retention after 1000 cycles". At 63 Wh/kg, it also demonstrated a high energy density. Over 1000 cycles, the MoS_2-rGO heterostructure-based binder-free electrode demonstrated capacitance retention "with a specific capacitance of 387.6 F/g at 1.2 A/g current density" [102].

Polymers are an ideal material for pseudocapacitors because of their high capacitance, which is a result of their multiple redox states and improved electrical conductivity. The electrochemical characteristics of "the MoS_2-Polycrystalline (PANI) nanocomposite" are excellent [103]. The hydrothermal approach was used to create "the MoS_2/polyaniline sandwiched nanosheets (MoS_2/PANI SNs)". When PANI is intercalated into (002) MoS_2 interlayers, the result is expanded layers and enhanced electron transport, two crucial aspects of the composite electrode.Under SEM, a microflower-like shape that resembles virgin MoS_2 is seen. "After 16,000 cycles, the MoS_2/PANI SNs electrode" maintains 86.6% of its capacity, which is longer than that of pure MoS_2. A polyaniline/MoS_2 nanosphere composite in the form of a three-dimensional sponge was made on carbon paper using a hydrothermal process and polyvinylpyrrolidone (PVP) [104]. Using cyclic voltammetry at a current density of 1A/g, the composite electrode revealed "a specific capacitance of 605 F/g". After 1000 cycles, the electrode maintained 88.6% of its capacitance, demonstrating exceptional cyclic stability "with an energy density of 53.78 Wh/kg and a power density of 0.4 kW/kg". A MoS_2/PANI nanocomposite electrode with excellent conductivity was developed by Wang et al. [105]. Three times the PANI electrode's specific capacitance, 390 F/g, was observed "at a current density of 0.8 A/g". MoS_2/PANI nanocomposites have a greater electrical conductivity value (2.38 S/cm) than both pure MoS_2/PANI (0.109 S/cm) and restacked MoS_2 (0.0137 s/cm). At a current density of 0.5 A/g, a MoS_2/PANI nanopallet

electrode produced "a specific capacitance of 476 F/g, with a 53% weight deposition of PANI on MoS_2". The constructed supercapacitor demonstrated "an energy density of 35 Wh/kg and 81% cyclic stability after 8000 cycles at a power density of 335 W/kg" [106].

At a current density of 0.5 A/g, one hydrothermally synthesised "graphene-like MoS_2 macroporous PANI nanorod (MPN) demonstrated a specific capacitance of 602.9 F/g". At a power density of 6000 W/kg, the MPN also demonstrated a "high energy density of 43.3 Wh/kg and an 86.7% capacitance retention over 2000 cycles" [107]. Chang et al. [108] used a simple hydrothermal process to create the MoS_2/ppy nanocomposite. Compared to pure MoS_2, the specific capacitance was higher "at a current density of 1 A/g, at 307.5 F/g". Tu et al. [109] looked at how the weight ratio affected the MoS_2/ppy electrode's electrochemical performance. At a scan rate of 10 mV/s, weight ratio 1/0.5 demonstrated "a maximum specific capacitance of 182.28 F/g" with 80% cyclic stability over 1000 cycles. A bigger surface area electrode worked better.

A volumetric capacitance of 245 F/cm^3 was demonstrated by the MoS_2/PANI/CNT symmetric supercapacitor device with "an energy density of 0.013 Wh/cm^3 and a current density of 0.3 A/cm3" [110]. Commercially available activated carbon electrochemical capacitors with capacities of 2.75 V/44 mF were outperformed by this supercapacitor. The MoS_2/rGO/PANI electrode was developed by Li et al. [111]. The SEM picture showed that nanowires had formed when aniline was deposited into the MoS_2/rGO composite's uneven surface. "Majumdar et al. [112] used the in-situ chemical oxidation synthesis" approach to create a polyindole/carbon black/MoS_2 composite. Over 5000 cycles, 92.3% capacity retention was attained, and at a current density of 1 A/g, the electrode showed "a specific capacitance of 442 F/g". "Zhang et al. [113] used MWCNT/PANI/MoS_2 hybrid electrode polymerisation" in conjunction with a hydrothermal method. During 3000 cycles, the electrode exhibited cyclic stability of 73.71% and "a specific capacitance of 542.56 F/g at a current density of 0.5 A/g".

Using exfoliated graphite carbon as the cathode and FeS_2/MoS_2 nanosheets as the anode, "Wang et al. [114] created a solid state asymmetric supercapacitor". The electrode showed "high specific capacitance (495 mF/cm^2 and 394 mF/cm^2) and higher conductivity compared to pure MoS_2 (132 mF/cm^2 and 218.1 mF/cm^2) and FeS_2 (315 and 285.5 mF/cm^2)".

Future prospective

Controlled precursor concentrations should be used to induce fractures or flaws on the nanosheets in order to investigate electrochemically active edges of MoS_2 sites. Among the numerous benefits of the MoS_2/Graphene hybrid electrode over other hybrid electrodes are its low cost, simplicity of manufacture, excellent chemical stability, improved conductivity, and "enhanced conductivity between and among particles". The carbon material's surface functional groups aid in ion and electron mobility during reactions and enhance its wettability and hydrophilicity. Therefore, the hybridisation of graphene and MoS_2 gives the composite structure exceptional electron accessibility.

CONCLUSIONS

In present study it has been concluded that MoS_2 and its composites can be synthesized using different physical as well as chemical methods. The prepared MoS_2 and its composites found significant application in supercapacitor as an electrode. The performance of the electrode originated from the material size as well as morphology which are strongly based on preparative parameters. In addition to this supercapacitance of the MoS_2 and its composites was established due to the nature and concentration of electrolyte.

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Data sets generated during the current study are available from the corresponding author on reasonable request.

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