The role of 2D material families in energy harvesting: An editorial overview

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The ever increasing proportion of an energy consuming society and the boost in industrialization accelerated the depletion of fossil fuel based energy sources at an alarming rate. This emphasizes the necessity of sustainable energy generation and storage to meet the daily energy demands. But, these alternative renewable energy sources like solar and wind power are intermittent and highly depend on weather, place and individuals. This creates the inevitability of suitable energy storage devices like batteries and supercapacitors. The interfacing of energy storing devices is required to maintain the supply chain equilibrium, power efficiency, regulate power fluctuations and reduce pollution. Besides, the boom in electric mobility and consumer electronics also require uninterrupted power supply. Hence, in the upcoming years the energy storing devices play a vital role in addressing the energy crisis. Innovations in new materials and technologies will be the core area of research and development in the coming future. 2D materials like graphene, transition metal carbides and nitrides (MXenes), transition metal borides (MBenes) and so on are the new class of materials among them MXenes are getting more attention in energy storage owing to its exceptional properties.

The energy demands of the entire globe are increasing day by day. For now, the key energy source is from fossil fuels, and it is not only having a large impact on the environment but depleting fossil fuel resources are causing energy crisis. This situation emphasizes the requirement of clean and sustainable energy generation and storage while meeting the criteria of eco-friendliness. The ever-developing IT sectors, industrialization and new boom of electric mobility necessitates the requirement for energy storage devices with higher efficiencies. The renewable resources of energy like Solar and wind are intermittent, in addition, the use of energy and the need for energy depend on the weather, place and individual needs. Therefore, an interfacing via suitable energy storage means in necessary, furthermore, to maintain supply–demand equilibrium, avoid electric fluxes, reduce blackouts during peak demand, reduce environmental pollution, and improve power grid efficiency [1–3]. According to the current situation, the entire world is going through a COVID-19 pandemic and other conflicts, which creates uneven impacts across all sectors. On that basis, the world energy council developed four plausible scenarios for 2024: Pause, Rewind, Fast-Forward, and Re-Record. For a better future, energy devices having high power densities and current densities should be developed, and that is the current motto of entire energy storage organizations. In the upcoming years, energy storage devices will be the core of research and development and green synthesized energy materials including cellulose [4] are explored. Energy storage devices
such as batteries, supercapacitors, and energy conversional devices such as fuel cells are getting increasing attention. The quest for high-performance energy storage devices and materials is a long-sought-after goal of modern materials science. The materials used for the devices’ fabrication have a huge role. The better combinations of materials produce a better device. In this sense, two-dimensional materials families such as graphene, transition metal dichalcogenides, phosphorene, metal oxides and hydroxides, transition metal carbides and nitrides (MXenes), transition metal borides (MBenes), metal–organic frameworks (MOFs), and so on, have become important due to their specific characteristics, including molecular thickness, high specific surface area, and tunable physicochemical properties dependent on the structure, composition, and functionalization. Currently, 2D materials and their composites have been widely explored in electrochemical energy devices and energy conversion systems.

Supercapacitors; emerging field of electro chemical energy storage device

Supercapacitors have gained much more attention both academically and industrially and 2D materials can optimize the power performance of these devices at multiple levels [5, 6]. As compared to batteries, they have benefits like prolonged cycle life and a very simple charge circuit is needed, maintenance is comparatively free and much safer to use [7]. A good supercapacitor device can be fabricated by designing a good combination of electrode and electrolyte. Supercapacitors are generally known as electrochemical double-layer capacitors. State-of-the-art technology has changed the energy industry into the main stream, which has resulted in numerous discoveries [8]. Supercapacitors are classified as electric double layer capacitors or pseudocapacitors based on their mechanism. In EDLCs, the capacitance is derived from electrostatic charges collected at the electrode/electrolyte interface. Instead, the energy storage takes place by Faradaic redox reactions in the pseudocapacitor. There will be an electronic charge transfer between the electrodes and the electrolyte. In many cases, the maximum charge in both types of devices is connected to the electrode surface area that is available to the electrolyte ions [9]. At the present time, hybrid supercapacitors are more attractive than others because they are more efficient due to the presence of two types of electrodes and mechanism. Stacking 2D materials with different properties into van der Waals heterostructures improves electrode activity. These combine the benefits of the individual components to overcome certain boundaries. The good electrical conductivity of graphene, the chemical flexibility of metal dichalcogenides and other 2D materials are getting more attention for supercapacitor electrode fabrication. Fig. 1 shows the schematic structures of typical 2D materials which are used to make composites with different materials.

In supercapacitors, MXene-based electrodes, specifically the free-standing films made from MXene, have shown great promise for supercapacitors, e.g.: Wang et al. have synthesized a PANI/MXene composite, when used as electrode material it produces high energy density supercapacitor with a capacitance of 337.5 F g⁻¹ at 1 A g⁻¹, and the capacitance of the devices can endure 97.6% after 10,000 cycles [11]. Yun et al. [12] fabricated wire-shaped SCs by mixing rGO with Ti₃C₂Tₓ MXene through the “bottom-up” layer-by-layer assembly process and showed outstanding areal capacitance (40.8 mF cm⁻²), volumetric capacitance (2193 F cm⁻³), and specific capacitance (237 F g⁻¹) with a wide voltage range (0–1.2 V). When researching the 2D materials related works done in supercapacitors, the majority of the research was done on MoS₂ and other metal sulfides, followed by dimetal selenides. A few studies on metal telluride-based supercapacitors have been published. Therefore, more prominent and comprehensive research work on the modified 2D material-based electrodes is ongoing [13].

Batteries

With the growing energy demand, there is an urgent need for efficient, low-cost, lightweight, and environmentally benign energy storage devices with high storage capacities. In this context, batteries are widely adopted in modern-day electronics, working as the main power sources for portable electronics and electric vehicles. Recently there is a great research effort on 2D materials i.e., graphene and its analogues, as electrodes for batteries due to their combination of high surface-to-volume ratio and better electrochemical properties [14]. Graphene analogues (GAs) are materials that have a similar structure to graphene, it does include transition metal dichalcogenides (TMDs), transition metal oxides (TMOs)/hydroxides (TMHs), metal sulfides, phosphorenes, MXenes, siliences, etc. [15]. Remarkable progress has been made using GAs in lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and other kinds of batteries. Schematic illustration on some important classes of Li based batteries are shown in Fig. 2.

Lithium-ion batteries

LIBs are considered the most widely used energy storage device in recent years. Significant research advances have been made in 2D materials in the development of next-generation LIBs. Earlier, lithium metal was used as an anode material because of its high energy density. Safety issues emerged from dendrite formation during cycling and, lithium metal was replaced by graphite in 1981 [16]. Still, graphite is the widely employed anode material for LIB due to its high coulombic efficiency and good cycling performance. However, due to the poor lithium-ion diffusion rate (10⁻⁸ cm² s⁻¹) and low theoretical capacity (372 mA h g⁻¹), there is a need for new electrode materials. Numerous materials were explored
Overview

in LIBs including metals, metal oxides, and graphene. Among these GAs, are considered a promising material for LIBs offering higher capacity than traditional graphite material.

Graphene-based materials have found application in LIBs due to its better electrochemical properties. 2D structure, heteroatom defects, and better electrode/electrolyte wettability improved ionic conductivity of graphene enable faster lithium-ion diffusion and electron transfer. Hu et al. [17] prepared graphene branched graphene nanocapsules with in situ formed graphene sheets (GC-Gs) as anode material in LIBs. The edges and defects associated with these GC-Gs facilitate lithium-ion diffusion. It is found that hybridization of graphene with inorganic material improves the rate capability and cycling stability of graphene in LIBs. Xiong et al. [18] reported the synthesis of ZnMn2O4-graphene hybrids for LIBs, which exhibit high specific capacities and cycling stability. 2D transition metal oxides (TMOs) are also a good electrode material for LIBs due to their good redox activity. TMOs show reversible redox reactions with lithium, TMOs such as Fe2O3 [19, 20], V2O5 [21], Nb2O5 [22], and TiO2 [23] are widely used as electrode material in LIBs. Fe2O3 is a typical TMOs, possesses a high theoretical capacity (1006 mA h g⁻¹), and is considered a promising anode material for LIBs.

2D structure of TiO2 has low volume expansion upon lithium insertion, good stability, and low lithium plating. Besides TMOs, transition metal dichalcogenides (TMDs) provide an ideal metal framework to store lithium-ions in LIBs. Hwang et al. [24] reported disordered graphene-like MoS2 nanoplates by the solvothermal method. MoS2 plates show high lithium storage capacity and good electrochemical performance. Recently, a new class of materials named MXenes was explored in LIBs. MXenes combine the unique properties of metallic conductivity and a low diffusion barrier against metal ions. Transition metal phosphates (LiMPO4) have also attracted increased attention nowadays due to their environmental friendliness and low cost. Zhao et al. [25] prepared LiFePO4 nanosheets with a thickness of 30–60 nm by the

Figure 1: Schematic of typical 2D materials applied in energy storage devices [10].
solvothermal process using diethylene glycol as solvent. The LiFePO_4 showed improved electrical conductivity and a low diffusion path for lithium-ion. The LIB exhibited better rate capability, high volumetric energy density, and excellent cycling stability.

**Lithium–sulfur batteries**

Lithium–sulfur (Li–S) batteries composed of sulfur cathode and metallic Li anode having very high energy density (2800 Wh L\(^{-1}\)) is found to be suitable alternative for Li-ion battery \[26\]. The low cost of sulfur, its natural abundance and less toxicity further makes Li–S battery as promising candidate for next generation sustainable energy storage devices \[27\]. However, the low cyclic stability and poor Coulombic efficiency of sulfur limits its commercialization and widespread applications to a greater extend. Some of the recent studies shows that 2D materials can address these issues to a greater extend by utilizing its interlayer spacing and abundant active sites \[28\] MXenes and graphene were successfully utilized to modify the cathode and anode material of Li–S batteries to enhance its electrochemical performance \[29, 30\]. Nazar et al. \[31\] recently reported the use of MXene as a sulfur host material and the device shows enhanced capacity retention of 80% for 400 cycles. Similarly, Jackson et al. reported a new design concept of graphene-sulfur composites for the fabrication of high performing Li–S battery and the device shows an excellent specific capacity of ~ 600 mA h g\(^{-1}\) and low energy decay of less than 15% over 100 cycles \[31\].
Sodium-ion batteries

Sodium-ion batteries (SIBs) gained increased attention in recent years with the development of new materials. 2D materials hold a great promise in producing SIB with better performance than earlier. Graphene and graphene-based composites improved the gravimetric capacity and energy density of SIB due to their high surface area, large ion storage capacity, and high electrical conductivity. Wang et al. [32] reported the use of reduced graphene oxide as an anode material in SIB which showed good rate capability and better cycle life. Layered transition metal oxides (TMOs) are also important cathode materials for SIB, which showed high specific capacity, and high working voltage. TMDs such as MoS2, MoSe2, and SnS2 have also found application in SIB because of their unique physical and chemical properties. David et al. [33] fabricated a hybrid of MoS2 and rGO flakes as a flexible electrode in SIB. This flexible electrode showed good electrical conductivity and fast storage and release of sodium ions at high C rates.

Recently a large family of 2D materials, called MXenes found applications in energy storage devices. They are good electrical conductors and can effectively store metal ions by intercalation chemistry that occurs in interlayer spaces. Dall’Agnese et al. [34] demonstrated V2CT as a positive electrode in a sodium-ion capacitor. These devices reach higher energy density than electrochemical double-layer capacitors. Owing to the high operating potential and excellent thermal stability, metal ion phosphates are also reported to be promising candidates for SIB. Recently Zhu et al. [35] studied VOPO4 nanosheets for both LIB and SIB which found to have 2D channels for lithium and sodium diffusion. VOPO4 possesses high energy density than LiFePO4 and a theoretical capacity of 166 mAh g⁻¹. In order to facilitate sodium ion diffusion, Li et al. [36] reported the interlayer expansion of intercalation hosts. Based on this, poly (ethylene oxide)—intercalated MoS2 composites were developed which exhibited a theoretical capacity of 225 mAh g⁻¹ and a current density of 50 mA g⁻¹.

Magnesium ion batteries

Rechargeable magnesium ion batteries have been considered as promising battery technology for future energy storage. Magnesium metal has favorable characteristics of a metal anode such as high specific volumetric capacity, bivalency, and high energy density. There are extensive studies carried out in developing rechargeable magnesium ion batteries for real-world applications. But it is still in its infancy due to the lack of practical electrodes and electrolytes. Recent research has shown that 2D nanomaterials such as layered TMDs found application in MIB electrodes. Liu et al. [37] reported carbon intercalated MoS2 nanosheets as electrode in MIBs, which showed a discharge capacity of 118.8 mAh g⁻¹ after 50 cycles. Later Liang et al. [38] developed an interlayer expansion method to increase the magnesium ion diffusion in MoS2. The material with different interlayer spacing exhibited different electrochemical performances.

Metal-air batteries

Metal air battery (MAB) is a class of electrochemical cell which possesses very high theoretical energy density found a major attention compared to LIB in recent times since it can perform even in open air atmosphere [39]. There are different types of metal air batteries like Li-air, Zn-air, Al-air, Fe-air and so on. Among these the Li-air and Zn-air batteries are getting more attention because of their better capacity and energy density. The structural design of MAB is combination of conventional battery and fuel cells which contains four main components such as air-breathing cathode, metal anode, electrolyte, and separator [39]. Compared to other battery technologies the MAB technique is cheaper due to the low material cost. One of the main drawbacks of MAB is there low energy conversion efficiency of cathodic reduction [40]. The role of 2D materials in MAB was investigated and found interesting results in their electrocatalytic activity. Wang et al. reported the enhanced electrocatalytic activity of Zn air battery through the incorporation of 2D bimetallic Co3FeN nanosheets [41]. This Co3FeN employed Zn air battery shows a maximum power density of 108 mW cm⁻² and better life cycle of 900 cycles [41]. Similarly, Xia et al. reported the fabrication of a flexible solid state Zn air battery with better power density (223 mW cm⁻²) and life cycle using metal–organic framework derived 2D nitrogen-doped carbon nanotubes/graphene hybrid electrocatalyst [42].

Redox flow batteries

Redox flow batteries which store energy through electrochemical redox reaction of working fluids are emerged as a new competitor for LIB due to its safer operation, longer life cycle and advanced electrochemical performance. The history of redox flow battery starts way back from 70 s and among the different available redox flow batteries, one of the most developed one is the vanadium based battery [43]. Recently, the Li based flow batteries with better energy density and voltage window was developed. The main advantage of Li based redox flow batteries is that it combines the merits of both Li ion batteries and redox flow batteries which aid to attain better electrochemical performance [44]. The basic difference of energy storage mechanism of redox flow battery compared with other batteries is that, in redox flow energy storage occurs as the
result of the chemical components dissolved in a liquid within the system and an external reservoir [45]. In redox flow batteries also the 2D materials are used extensively in recent years to improve its electrochemical performance. In recent years, Kumbur et al. reported the use of Ti$_3$C$_2$T$_x$ MXene as an electrocatalyst for Vanadium redox low battery and the results showed remarkable enhancement in energy efficiency (7%) and electrolyte utilization (22%) [46]. The enhancement in properties were due to the improved surface area and electro kinetics imparted by the MXene additive [46]. Likewise, Bonaccorso et al. reported the use of texturized graphitic electrodes in vanadium redox flow batteries and it was further improved by graphene coating. The fabricated vanadium redox flow batteries showed a high rate capability after graphene coating [47].

Closing remarks
As a consequence of the energy crisis and related environmental issues, there is an urgent need for development of sustainable energy storage devices with higher efficiencies for the future. 2D nanomaterials like graphene nanosheets and related composites, layered transition metal oxides, transition metal dichalcogenides, and MXenes are of great research interests in recent times due to their excellent properties such as high conductivity, environmental friendliness, high porosity and surface area, better ion storage capacity (interlayer spacing), and better electrochemical performance. These specific properties of 2D materials can offer better ion diffusion channels as well as ion storage sites which enhances the performance of supercapacitors and batteries including Li-ion, Na-ion, Mg-ion and so on. Hence, the introduction of graphene and other 2D nanomaterials in energy sectors tends to meet the demands of energy storage system by enhancing the overall energy density and power density through more sustainable and environmentally friendly manner.

Data availability
The data used to support the findings of this study are included within the article.

Declarations
Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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