The Future of Graphene Oxide-Based Nanomaterials and Their Potential Environmental Applications: A Contemporary View

Subhendu Chakroborty, Pravati Panda, and Suresh Babu Naidu Krishna

Abstract Environmental safety is vital to life on Earth. Environment and life are interconnected like two sides of a coin. Pollution is a serious challenge in both developing and developed nations. Rapid rise in human civilization, together with metrological works and industrialization, affects the environment. Due to the excessive release of heavy metal ions, air, water, and soil-borne diseases as corona, cholera, cardiovascular issues, chronic conditions, and cancer increase. Different research organizations use several ways to combat environmental problems. Nanotechnology-based solutions are cost-effective and efficient. Nanomaterials' multifaceted applications revolutionize science. Its particle-to-size ratio gives a wide surface area with several reactive sites. Carbon-based nanomaterials like graphene, fullerene, carbon nanotubes, graphene oxide, carbon-based quantum dots, etc., have received a lot of attention due to their application to combat environmental issues. Through this chapter, we want to draw researchers' and academics' attention to recent trends and applications of graphene oxide based photocatalysts in degradation of organic dye pollutants, biomedical significance, challenges, and future perspectives which will improve the development and application of more multidimensional nanomaterials to human health and for the development of biodiagnostics.

Keywords Dye pollutants · Graphene oxide · Environment · Photocatalyst · Plasmonic nanostructures · Therapeutics

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Nomenclature

Ag/AgCl	Silver /Silver chloride
As	Arsenic
AmGO	Amino functionalized graphene oxide
BET	Brunauer, Emmett and Teller
BMIMCIIL	1- butyl 3- methyl imidazolium chloride
CGA	Cellulose-graphene oxide composite aerogel
CGO	Aerogels of cellulose and graphene oxide
CS	Chitosan
CM	Ceramic membrane
CMC	Carboxymethyl cellulose
CRZ	Carbendazim
CV	Cyclic voltametric
DCC	*N, N′*-dicyclohexylcarbodiimide
DLVO	Derjaguin–Landau–Verwey–Overbeek (DLVO) theory
FSC	Furniture scraps charcoal
FTIR	Fourier Transform Infrared
EDX	Energy-dispersive X-ray spectra
GGO	Gd_2O_3-doped graphene oxide
GO	Graphene oxides
GO/LDH(GL)	Graphene oxide/layered double hydroxides composites
GO/GCE	Graphene oxide (GO)-based glassy carbon electrode
GO-coumarin (GC)	Graphene oxide (GO)–coumarin (GC)
GO-SiO_2	Silica–graphene oxide nanocomposite
HGAAS	Hydride generation atomic absorption spectroscopy
hrGO	Hydrothermal reduction graphene oxide
hrGO-Trp	Tryptophan cross-linked hrGO membranes
IL	Ionic liquid
LDH	Layered double hydroxides
LOD VALUE	Limit of detection
M/GO	Graphene oxide based magnetic nanocomposite
MB	Methylene blue
MG	Malachite green
MGO	Magnetic graphene oxide
mGO	Multilayer graphene oxide
MO	Methyl orange
PPD	*p*-Phenylenediamine
PPy	Polypyrrole
PVC	Poly vinyl chloride
PS	Polystyrene
RB	Rose Bengal
rGO	Reduced graphene oxide
Rh6G	Rhodamine 6G

SEM	Scanning electron microscopy
SWV	Square wave voltammetry
TEM	Transmission electron microscopy
TGA	Thermogravimetric analysis
T-GO-C	Thymine-GO-Carbohydrazide
TSC	Thiosemicarbazide
UV-Vis	Ultraviolet-visible
XRD	X-ray diffractometer
Zr-MnO_2-RGO	Zirconium (Zr) decorated with manganese dioxide (MnO_2) nanoparticles-functionalized reduced graphene oxide (RGO)

1 Introduction

Nowadays, the present generation is threatened by increasing environmental pollution, which results in a large variety of life-threatening ailments such as cardiac disease, cancer, diabetes, brain ham rage, and kidney failure [1, 2]. It is now becoming a serious matter of concern both for the developed and developing countries. Environmental pollution is not only affecting human civilization but also the aquatic animals are also suffering a lot [3–5]. To maintain high economic profile, man is setting various types of industries and companies which though make us enrich but simultaneously it causes high rate of air, water, and soil pollutions [6]. Release of highly poisonous gases cause air pollution and discharge of contaminated water goes to the water bodies and fields which simultaneously caused water and soil pollutions [7–9]. Polluted water containing organic dyes, heavy metal ions, nuclear wastes, agricultural wastes, etc., transit into the water bodies which makes a layer upon them as a result it limits the penetration of sun rays into it by which death of aquatic animals occurs as well as they also suffer from diseases due to lack of sunlight [10]. People when take the affected fish in food and water, they also get suffered from multiple waterborne diseases. Moreover, the growth of crops is also getting hampered due to loss of biogenic bacteria. Due to industries, the soil will get covered by a layer of toxic metal ions which also hampered human civilization and environment [11]. In view of the growing environmental pollution, people are developing multiple ways to tackle the challenge and invent new ways to fight the environmental problems and survive in it [12–15]. Though the developed strategies are helpful, but due to growing resistance developed by the microorganisms for different kinds of old protocols, we also need to be more attentive and work more o invent new, innovative, and cost-effective protocols which is the call of the day.

Development of nanotechnology brings several opportunities for scientists as well as for the society [16–18]. Furthermore, nanotechnology has captured the attention of people all over the world because of its superior mechanical strength, small particle size with large surface area, chemical resistivity, high thickness, and other properties that allow it to be implemented in a variety of fields ranging from everyday life to space technology [19]. Among the varieties of nanomaterials available, graphene oxide is quite attractive because of its large surface area which can be easily functionalized by different kinds of groups which simultaneously enhances its reactivity, selectivity, and hydrophilicity [20]. The procedures for the creation of its many different derivatives are likewise quite straightforward. These procedures use reagents that are economical and far less hazardous than traditional solvents. They also save time, are simple to deal with, and produce high yields. Consequently, it has found applications in a wide variety of contexts [21–23]. Numerous implications for the environment may be found in literature. Graphene oxides (GO) capture diverse pollutants such as dyes, heavy metal ions, microorganisms, and so on through non-covalent interactions such as pi-pi interactions, H-bonding, cation-pi interactions, van der Waals interactions, and so on [24–27]. The synthesis of many GO derivatives and their various environmental applications, such as the detection of dyes, organic pollutants, heavy metal ions, microbes, agricultural wastes, and other types of contaminants, are summarized in this chapter.

2 Potential Environmental Applications of Graphene Oxide-Based Nanomaterials

2.1 Synthesis and Removal of Heavy Metal Ions from Wastewater

Graphene oxide-based nanomaterials have a wide range of potential environmental applications due to their unique physical, chemical, and mechanical properties. By electrostatic self-assembly between negatively charged GO and a cationic nitrogenous coumarin-surfactant, the Peng research group designed and constructed the first photoreversible graphene oxide (GO)-coumarin (GC) composite. It was shown that exposing a GO/coumarin composite to UV light (at either 365 or 254 nm) photoreversible alters the morphological structure of the composite, hence improving its adsorption capacity and resolving the separation problem. Powerful Cd^{2+} adsorption capabilities (340.3 mg/g) are displayed by the GC composite [28].

Heavy metals poisoning in the water habitats has gotten worse because of quick industrialization. Therefore, it is critical to create improved heavy metal removal technology. For the adsorption of heavy metals from an aqueous solution, composite paper-like materials based on graphene oxide (GO) have been used extensively. Khan et al. used a resin-infiltration approach to create an advanced, highly ordered, and homogeneous polyvinyl chloride (PVC)/*p*-Phenylenediamine (PPD)/GO paper-like material for the first time. Layer-by-layer assembly, where the assembling components must interact significantly, is complemented by this approach (e.g., via hydrogen bonding or electrostatic attraction). The resulting PVC, PPD, and GO buck papers are extremely durable over a broad pH range and at high temperatures. They are efficient at removing Pb^{2+} from sewage water [29].

Abaszadeh's research group designed and synthesized MGO@APhen (magnetic graphene oxide (MGO) functionalized with 5-amino-1,10-phenanthroline (APhen) in the presence of *N, N′*-dicyclohexylcarbodiimide (DCC) as a novel nanomaterial by functionalizing the GO surface with Fe_3O_4 and 5-amino-1,10-phenanthroline. This nanocomposite possesses GO as a planar material that increases the reaction contact area, iron nanoparticles as a magnetic material that simplifies separation and Phen as a suitable ligand that binds to metal ions. The synthesized MGO@APhen was employed as an effective adsorbent for the adsorption of Pb^{2+} [30].

To prevent challenges in recovering GO powder after greener removal of heavy elements such as As (V), Pb (II), and Cr, Sodium Alginate (SA) and carboxymethyl cellulose (CMC) are used to produce granules of a graphene oxide nanocomposite doped with gadolinium oxide (Gd_2O_3). gGO-Gd_2O_3 is granular Gd_2O_3-doped-GO. gGO-Gd_2O_3 adsorbs 158.23 mg/g Pb (II) [31].

Lee and his coworker devised a simple technique for manufacturing magnetic Gd_2O_3-doped graphene oxide (GGO) for Pb (II)-contaminated water treatment. Active surface functional groups increase its adsorptive capacity over plain graphene oxide (GO) and iron oxide-doped GO. GGO performance is affected by pH, adsorbent dose, starting metal concentration, and rate-limiting kinetics on homogenous surfaces. Gd_2O_3 doping increased GO's Pb adsorption capacity to 83.04 mg/g (II). Langmuir's equation says GGO's optimal Pb^{2+} uptake capacity is 83.04 mg/g. Also compares GGO's Pb^{2+} adsorption capability to related materials [32].

Barik et al. synthesized silica–graphene oxide nanocomposite (GO-SiO_2) nanocomposite via room-temperature using 1- butyl 3- methyl imidazolium chloride (BMIMCl IL). This two-step approach disperses GO in ionic liquid (IL), then decorates the GO surface with silica using formic acid in IL. After repeated washing, this compound was employed to adsorb Pb (II) and As (III) ions from aqueous systems. Novel mesoporous nanocomposite absorbed 527 mg/g Pb (II) [33].

Abubshait's team utilizes modified graphene oxide-thiosemicarbazide (mGO-TSC) nanocomposite to detect Cu^{2+} elimination from aqueous solution. The GO picture showed a thin, homogenous layer. Transmission electron microscopy (TEM) images of mGO-TSC showed clustered entanglement zones of thiosemicarbazide (TSC) molecules across GO sheet surface. Adsorption studies show Freundlich isotherms. Kinetic investigations showed that adsorption is driven by a pseudo-second-order model via inter-particle diffusion. The improved adsorbent (mGO-TSC) was reused four times with 85% Cu^{2+} adsorption effectiveness. Metal ions adsorb more strongly on mGO-TSC than GO [34].

Li and his co-workers synthesized graphene oxide/layered double hydroxides GO/LDH (GL) composites and magnetic Fe_3O_4@GO/LDH (Fe_3O_4@GL) to adsorb Cu^{2+} from wastewater. GL (Cu^{2+}: 89.26 mg/g) showed a greater maximum adsorption capacity than Fe_3O_4@GL. The adsorption rate rose progressively from 0.01 g to 0.15 g in 20 mL solution, reaching equilibrium [35]. Electrostatic self-assembly of positively charged nitrogenous coumarin surfactant and negatively charged GO creates a photoreversible graphene oxide-coumarin composite. This photoreversible composite removes Zn^{2+} from wastewater [28]. In summary, graphene oxide-based nanomaterials can synthesize and remove heavy metal ions from wastewater, making water treatment more effective and sustainable. Graphene oxide-based nanomaterials have great adsorption capacity, selectivity, and stability, making them a potential remediation choice. However, more research must be conducted to optimize the production method and examine the environmental consequences of graphene oxide-based nanomaterials. Graphene oxide-based nanoparticles could revolutionize water treatment and contribute to sustainability with further development and optimization.

2.2 Heavy Metal Removal

A novel magnetic nanoparticles adsorption material based on GO, chitosan (CS), and polyethyleneimine was used to adsorb and remove heavy metals and anionic azo dyes from water. When combined with hydride generation atomic absorption spectroscopy (HGAAS) and Ultraviolet–visible (UV–Vis) to validate removal, the developed approach offers a platform for removing, analyzing, and determining harmful chemicals in aquatic ecosystems [36].

Inspired by the beautiful architecture of graphene, which has a high surface area and a wider range of oxygen-containing functionalities than other carbonaceous materials, the authors intend to use it as a useful candidate for metal ion adsorption. Considering this, graphene oxide-based nanoribbons (GONRs) were created using ultrasonication. The nanoribbons were successfully used for heavy metal ion adsorption in an aqueous environment, and the results showed that the nanoribbons were capable of absorbing As (V) from the waste water with 155.61 mg/g adsorption potential for As (V) in 12 min [37].

Hydrogels of A-GO (agar-graphene oxide) were produced through one-step jellification process and were applied for the selective removal of cationic dye Safranin-O and the drug chloroquine diphosphate. The morphology of the hydrogels was characterized through different spectroscopic measurements. The adsorption of the drug and the dye was confirmed by studying Freundlich and Sips isotherms and analyzed through Fick's diffusion equation and driving force models which exhibited $R_2 > 0.98$. Gradual increase in the pH increases the rate of adsorption. The developed hydrogels showed excellent potential adsorption when all of them were mixed in water with an adsorption value of $\sim$63 mg g^{-1} for chloroquine and 100 mg g^{-1} for safranin-O which was confirmed by Fixed-bed breakthrough curves. Mechanistically, the adsorbate gets adsorbed on the active site of the adsorbent through various types of interactions including electrostatic attractions, hydrogen bonding, or π-π conjugation interactions. In addition to this, the nanomaterial exhibited good reproducibility and recyclability and also successfully removed both the contaminants from water (Fig. 1) [38].

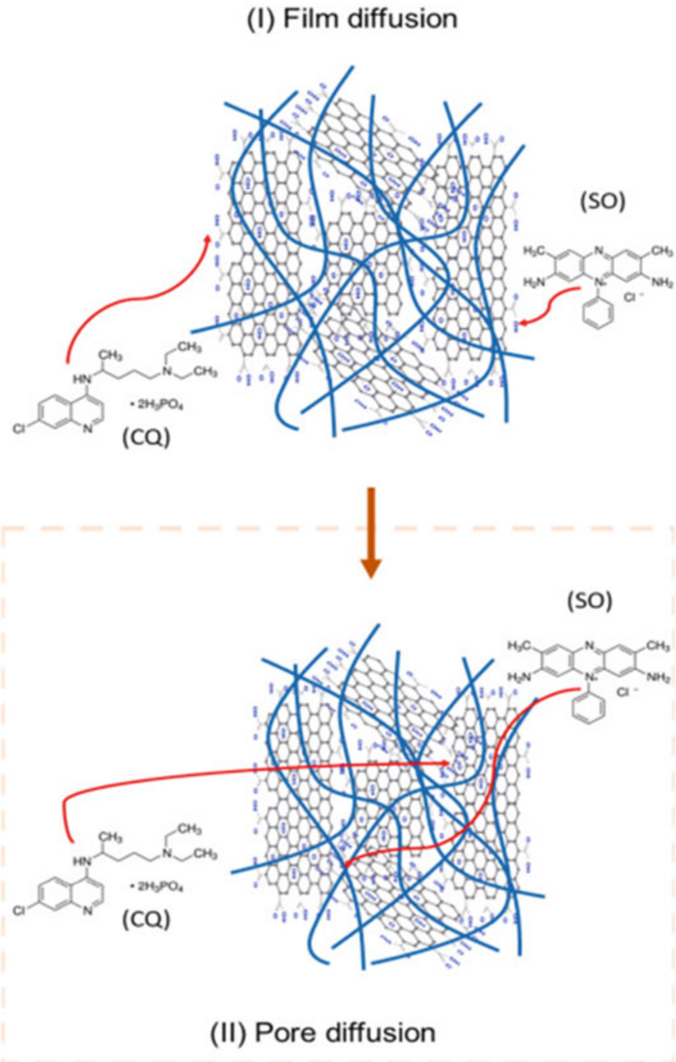

Fig. 1 Mechanism of adsorption. Reprinted with permission from [38]. Copyright (2023), Elsevier

Zirconium (Zr) decorated with manganese dioxide (MnO_2) nanoparticles-functionalized reduced graphene oxide (RGO) (Zr-MnO_2-RGO) based nanocomposite was synthesized by the doping of Zr and MnO_2 NPs on the surface of the RGO following an easy and convenient chemical pathway. It was applied for the selective detection of As(V) in the aqueous medium. The prepared nanocomposite was characterized through X-ray diffractometer (XRD), thermogravimetric analysis (TGA), scanning electron microscope (SEM), TEM, Fourier Transform Infrared (FTIR), Energy-dispersive X-ray spectra (EDX), etc. Fabrication of MnO_2 and Zr

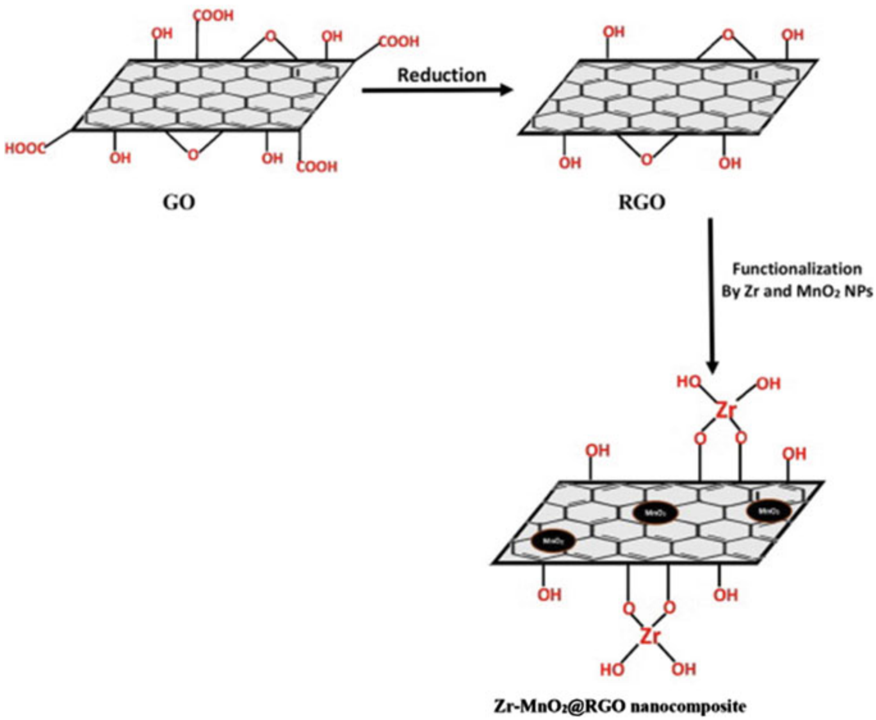

Fig. 2 Preparation of the Zr-MnO_2-RGO nanocomposite. Reprinted with permission from [39]. Copyright (2021), Elsevier

NPs simultaneously enhanced the specific surface area as well as adsorption affinity of RGO surface toward arsenic As(V). The optimum pH for the removal of As(V) was pH 4. The rate of adsorption was best analysed through Langmuir adsorption isotherm and followed pseudo-second order kinetics. The removal efficacy was found to be 98.5–99.3% in industrial and ground water. Moreover, it showed good recyclability and reusability (Fig. 2) [39].

2.3 Graphene Oxide-Based Nanomaterials for Removal of Organic Pollutants

Water scarcity is being made worse by a wide variety of organic pollutants that are found in industrial effluents, agricultural runoff, and home discharges. These pollutants are also responsible for the spread of water-borne diseases and have a negative impact on marine ecosystems and biodiversity. Immediate attention must be paid to the development of materials that are productive, environmentally friendly, and economical in order to eliminate organic pollution. Aerogels of cellulose and GO (CGO) were prepared from the fruit waste by gelatinization of cellulose and GO and were subjected for the purpose of wastewater treatment. H-bonding interaction between the GO and cellulosic skeleton generated porosity in the synthesized aerogel which helped for mass transfer and diffusion of the organic dyes present in the wastewater. The organic dyes were adsorbed at the surface-active site of the cellulose-graphene oxide composite aerogel (CGA aerogel). The highly porous (96.4%), ultra-light (0.018 g/cm^3), charge, size, and the surface-active sites play a significant role in the adsorption process. Mechanistically, it was proposed that electrostatic, dipole–dipole, π-π, n-π, cation-π interactions, and Yoshida hydrogen linkages made between the ample number of oxygen functionalities present on the CGA surface with the organic dyes are mainly responsible for the adsorption of the contaminants on the surface of the hydrogel. It displayed fast and highest cationic dye (methylene blue (MB), malachite green (MG), rhodamine 6G (Rh6G) adsorption ability over anion dyes (rose Bengal (RB) and methyl orange (MO)) due to the electrostatic interaction of the negatively charged O-atoms with the cationic dyes. The prepared aerogel was found to be an excellent candidate for the selective adsorption around >98% (MB dye) and rejection of organic contaminants from wastewater as well as it exhibited high recyclability and reusability. The adsorption tendency of the CGA toward the MB dye was found to be quite superior over simple activated carbon (46%) as well as GO powder (40%) (Figs. 3 and 4) [40].

Graphene oxide (GO) coated glassy carbon electrode (GCE) electrochemical sensor (GO/GCE) was designed, prepared by the fabrication of 2D GO over GCE and utilized toward the detection and estimation of concentration of Carbendazim (CRZ), a commonly used fungicide, in the water and soil samples. Cyclic voltammetric (CV) and square-wave voltammetry (SWV) techniques were applied for determining the voltametric behavior of the sensing material. The electro-oxidation of the CRZ followed a quasi-reversible reaction pathway with two protons and electrons

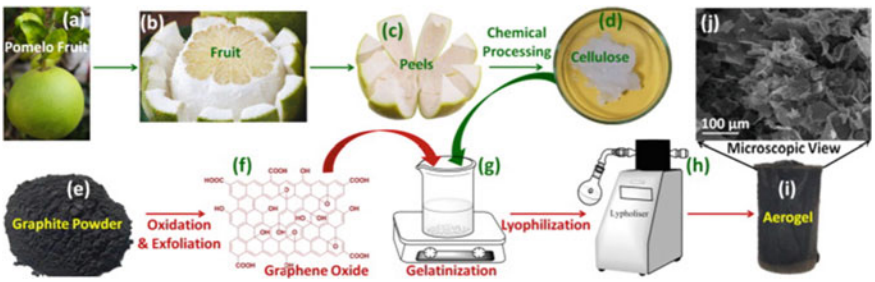

Fig. 3 **a** Pomelo fruit, **b** peeling of pomelo fruit, **c** peels, **d** cellulose extracted by chemical processing of fruit waste (peels). **e** Graphite powder, **f** representative chemical structure of GO, which is prepared by severe oxidation and exfoliation of graphite powder. **g** Gelatinization of GO with cellulose into a hydrogel. **h** Lyophilization of cellulose-GO hydrogel into CGA composite aerogel. **i** Digital photograph of CGA aerogel. **j** Microscopic view of aerogel demonstrating the porous structure. Reprinted with permission from [40]. Copyright (2022), Elsevier

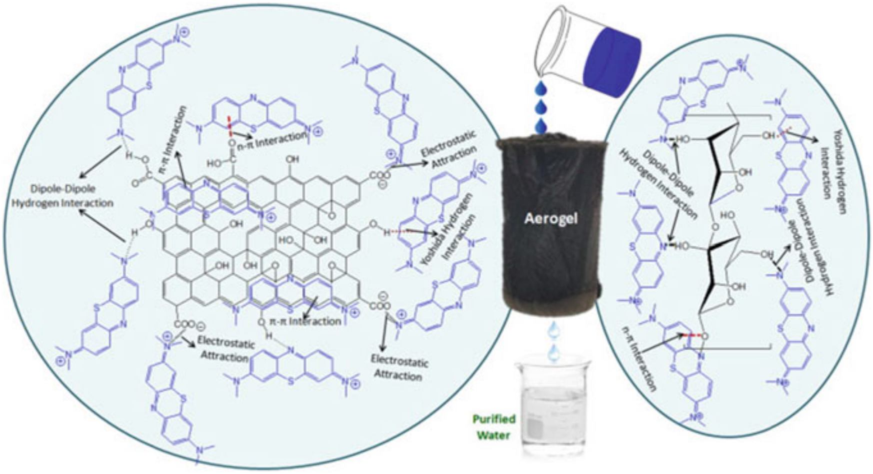

Fig. 4 Schematic representation of plausible interactions between active surface sites/chemical functionalities of CGA and MB dye molecules. Reprinted with permission from [40]. Copyright (2022), Elsevier

participation. An optimum response was recorded for GO/GCE was recorded at pH 4 when phosphate buffer solution was taken as the supporting electrolyte. It was able to detect very trace amount of CRZ present in the real samples and displayed a linear response was recorded for concentrations ranging from 1.0×10^{-7} M to 2.5×10^{-4} M. The limit of detection (LOD) value was found to be 1.38×10^{-8} M. The developed sensor displayed high selectivity toward the detection of CRZ in presence of other interfering ions and hence, can successfully apply for the estimation of CRZ in the water and soil samples (Fig. 5) [41].

Fruit waste, which generally accumulates as waste and causes environmental pollution, contains a huge number of natural reductants. Here the authors had taken advantage of the waste and reused it for the generation of highly porous adsorbent material for the effective adsorption of sulfamethoxazole, a type of antibiotic, in the aqueous environment. In this work, the authors have synthesized graphene by the biogenic reduction of GO by using the peel extracts of dragon fruit which served as a natural reductant. Betanin, a natural reductant present in the peel extract was extracted following an aqueous extraction process under optimal reaction condition, i.e., under suitable pH and kept it properly without disturbing its reducing potential. It was found that the biogenic natural reductant plays a promising role toward the reduction of GO following SN2 nucleophilic reaction pathway under a slight alkaline condition using phosphate buffer solution in 1 h. The prepared reduced graphene oxide (rGO) performed outstandingly and works as an electrochemical sensor toward the detection of antibiotic sulfamethoxazole in the aquatic medium. The silent merits of the developed process include cost-effectiveness, environmental friendliness, high stability, and quantitative production ability (Fig. 6) [42].

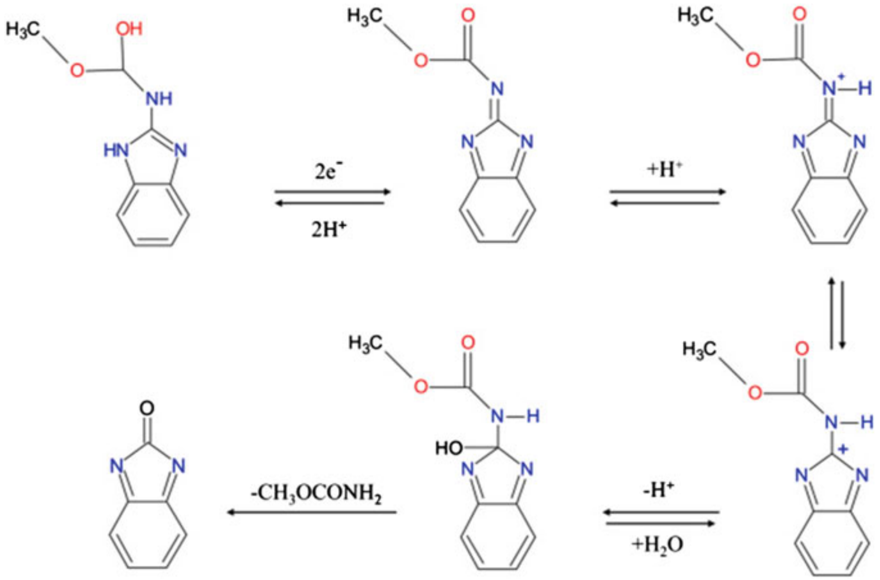

Fig. 5 CRZ electrode mechanism. Reprinted with permission from [41]. Copyright (2022), Elsevier

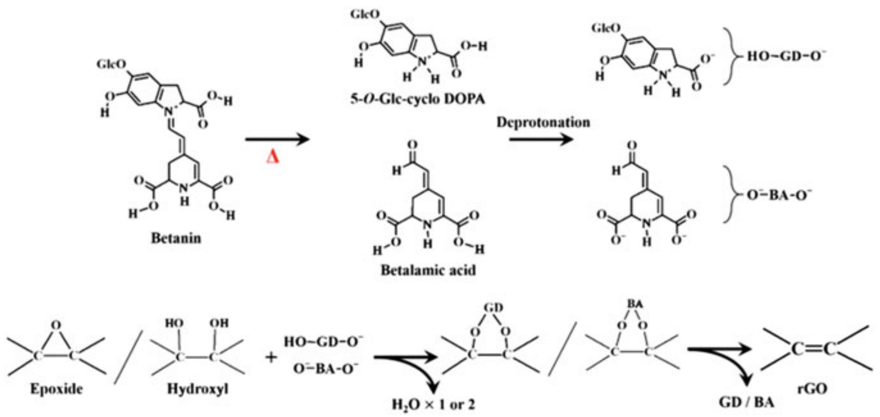

Fig. 6 Proposed reaction pathway for GO reduction by dragon fruit peel aqueous extract. Reprinted with permission from [42]. Copyright (2022), Elsevier

A multifunctional nanocomposite composed of GO-Fe_2O_3 was prepared and used as a sensing agent toward the dye detection in the water medium. The nanocomposite was prepared by mixing of clay and GO with Fe_2O_3 NPs and annealed under 550 °C to generate the fine structure of the nanocomposite. The nanocomposite was found to have a face-centered cubic like structure with an average particle diameter of 13.31 nm. It calorimetrically detects ascorbic acid when treated with ascorbic acid and uric acid using paper sensor. It worked as an excellent adsorbing material whereas displayed found to have low photocatalytic ability. The prepared Clay/GO/ Fe_2O_3 nanocomposite performed well toward the adsorption of the toxic dyes like methylene blue even in low concentration in the aquatic medium and followed 2nd order kinetics as confirmed through BET study. The surface adsorbing sites, electrostatic interactions, and porous nature govern the active adsorption and removal of MB dye from water samples (Figs. 7 and 8) [43].

GO fabricated polystyrene films as nanocomposite were designed and synthesized as electrospun. The GO was prepared through modified Hummers' process and was doped on the polystyrene(PS) fibers surface. The morphology and structure prepared nanocomposite were examined through XRD, SEM, TEM, FTIR, TGA, etc., which confirmed the successful incorporation of GO over the PS surface. The smooth surface area of the PS fiber facilitates the successful incorporation of GO on it which was confirmed by SEM analysis. The nanocomposite was found to be composed of ~87 wt.% PS and ~13 wt.% GO and hence both displayed the same thermogravimetric behavior as examined through TGA. After successful characterization, the dye was then subjected to study for their dye-adsorbing ability. It works as an excellent adsorbent toward the detection of MB dye in wastewater. It displayed outstanding adsorptive potential around 2.3 times more as compared to other reported adsorbing material and the simple PS membranes. It can detect the dye within 30 min

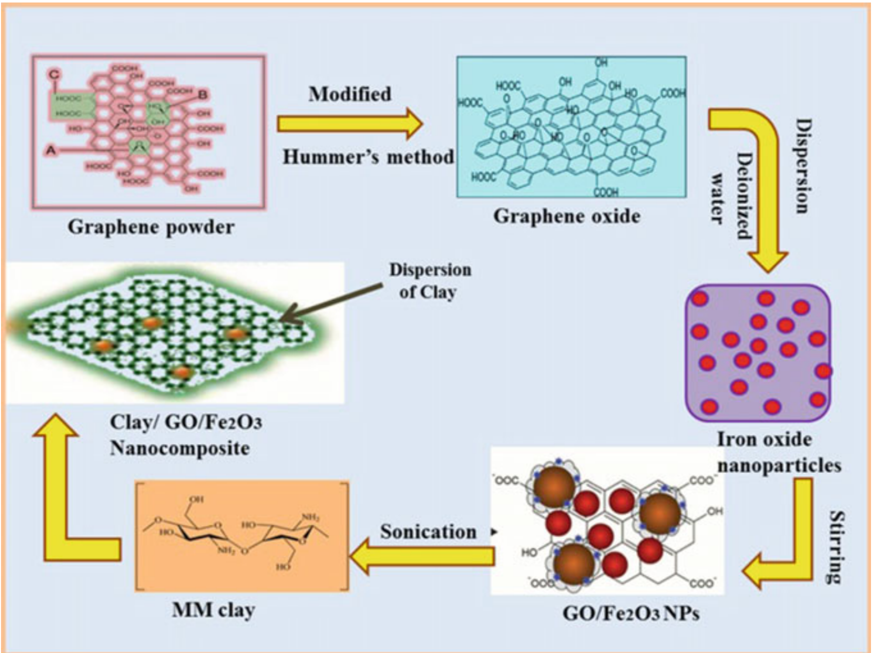

Fig. 7 Schematic illustration of synthesis of clay/GO/Fe_2O_3 nanocomposite. Reprinted with permission from [43]. Copyright (2022), Elsevier

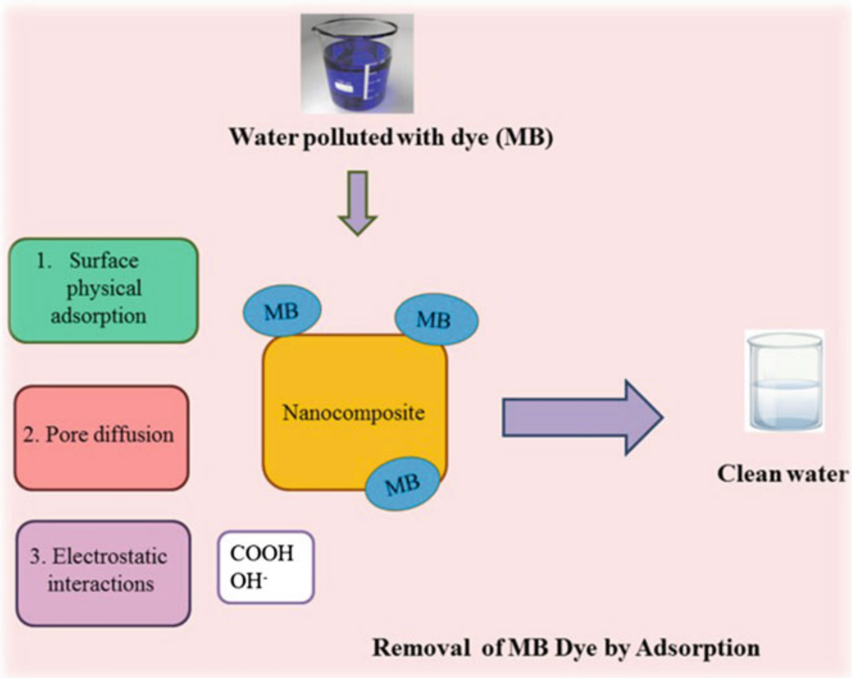

Fig. 8 Proposed mechanism for the removal of MB dye by Adsorption. Reprinted with permission from [43]. Copyright (2022), Elsevier

in the aqueous medium and has an adsorptive capacity 114 mg/g which is reached after 120 min. The adsorption process followed pseudo-second-order kinetics model which suggested 116 mg/g as the adsorptive capacity of the nanocomposite [44].

Furniture scraps charcoal (FSC) supported amino functionalized GO multilayer nanocomposite (AmGO) composite (AmGO@FSC) was prepared, well characterized, and subjected for the detection of organic dye in the wastewater. AmGO-FSC-based nanocomposite provided a two-way solution to tackle the environmental solution as a biogenic eco-friendly waste material was used to synthesize valuable nanocomposite to handle the raising water contamination problem. Also, due to the hydrophilic nature of the nanocomposite, it can be easily separated from the water medium. It possessed 54.35 mg/g maximum adsorptive tendency at monolayer with an equilibrium constant value of 0.76 L mg^{-1} as confirmed by Langmuir–Freundlich isotherm. The possible mechanism of adsorption was assumed to be governed by resistance to liquid–solid film and mass transfer in the bulk. Amino functionalization enhanced the adsorption tendency of the multilayer GO through pi–pi interaction and also by other possible non-covalent interactions. Cost-effectiveness, high adsorption potential (2 times more than FSC), great recyclability, and reproducibility even after six times of use were found to be the major advantageous features of the developed nanocomposite which can be applied as a profitable adsorbent of textile dyes (Fig. 9) [45].

To make a comparative study of the adsorbing tendency the authors synthesized of multilayer GO and magnetic GO-based nanocomposite through microwave-mediated Hummers' process and further examined their metal ion adsorbing tendency in the wastewater. The presence of increased inter-layer spacing along the c-axis of the prepared nanocomposite was confirmed through XRD analysis. Raman, SEM, and TEM confirmed the structure, quality, and morphology, i.e., presence of wrinkles on the surface of the nanocomposite. UV–*Vis* analysis suggested the presence of conjugated double bonds (C = C bond) and carbonyl (C = O) groups in the nanomaterial. The manufactured nanocomposite containing a large surface area around

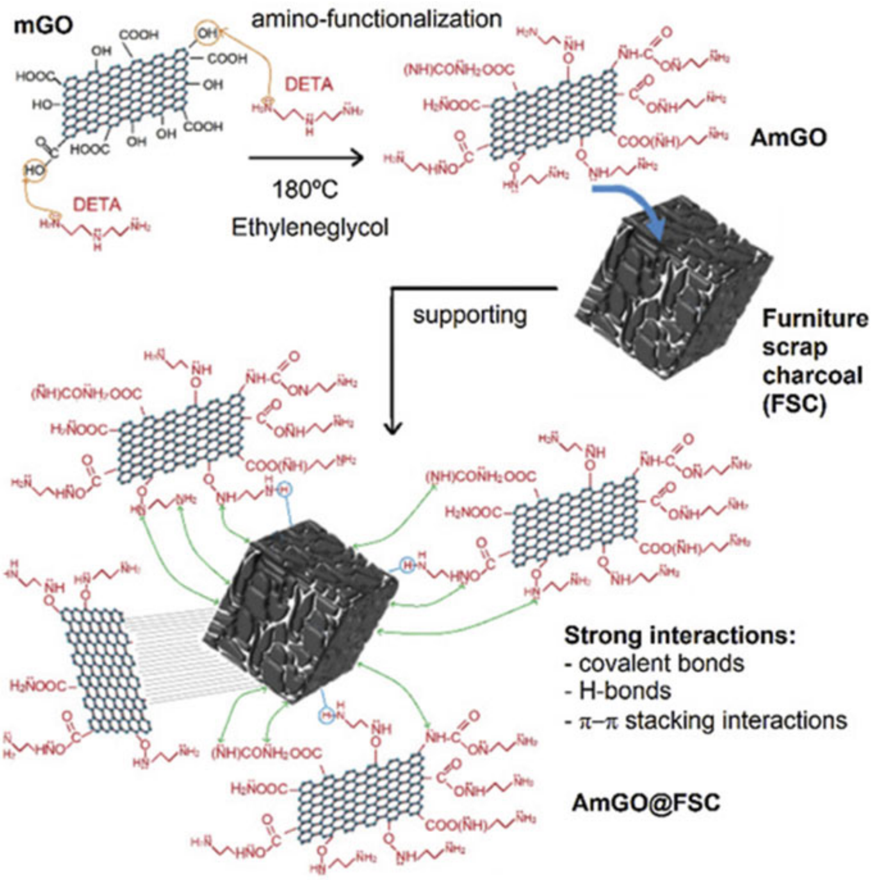

Fig. 9 Schematic representation of the supporting of AmGO over FSC structure. Reprinted with permission from [45]. Copyright (2022), Elsevier

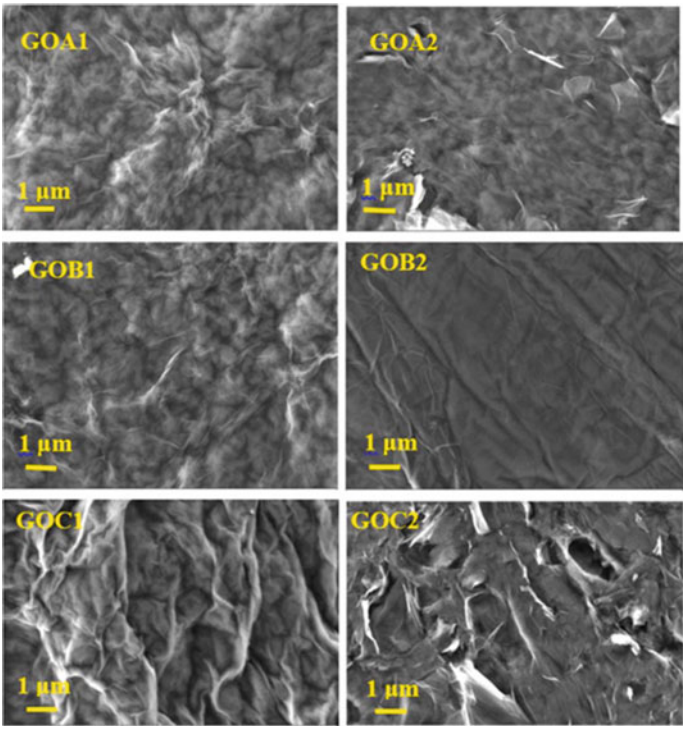

Fig. 10 SEM images of graphene oxide (GO) samples. Reprinted with permission from [46]. Copyright (2022), Elsevier

126 m^2/g with a huge quantity of surface active sites for the adsorption of the heavy metal ion was confirmed through BET analysis. Heavy metal ions like toxic Pb^{2+} and Cd^{2+} were found to be excellently adsorbed over the surface of the graphene oxide-based magnetic nanocomposite (M/GO). Experimental results suggested that prepared M/GO nanocomposite possessed superior adsorbance ability toward Cd^{2+} ion over simple GO nanocomposite (Fig. 10) [46].

2.4 Graphene Oxide-Based Membranes in Wastewater Treatment

Graphene-based membranes can afford numerous novel mass-transport properties that are not possible in state-of-the-art commercial membranes, making them promising in areas such as membrane separation, water desalination, proton conductors, energy storage and conversion, and many more. Significant progress has been made in the design of next-generation filtration and separation membranes using graphene materials. Hydrothermal reduction GO (hrGO)-amino acid membranes

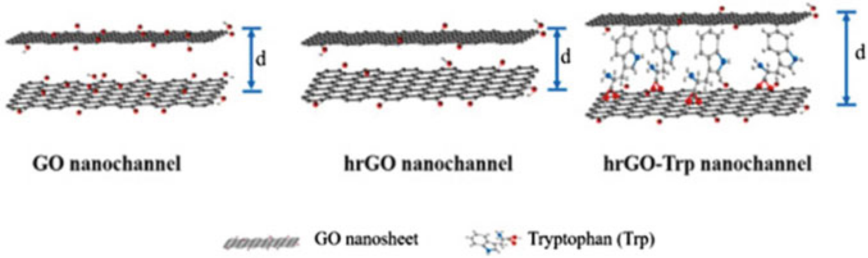

Fig. 11 Schematic illustration of separation mechanism through GO nanochannel, hrGO nanochannel, and hrGO-Trp nanochannel. Reprinted with permission from [47]. Copyright (2022), Elsevier

toward wastewater treatment were prepared by the fabrication of amino acid over the GO produced through hydrothermal reduction process. The water permeability ability of the prepared membrane was found to be excellent as well as it displayed good potential toward heavy metal ion rejection present in the wastewater. Tryptophan cross-linked hrGO membranes (hrGO-Trp) when treated with $FeCl_3$ solution showed 191.0 L m^{-2} h^{-1} bar^{-1} water permeability with 98.2% as rejection potential toward $FeCl_3$ which was around 4.4 times more than that of pristine GO membrane and other NF membranes. The developed membrane was found to have superior water permeability, highly stable, have long half-life, and also exhibited good heavy metal ion (Fe^{3+} ion) rejection ability (Fig. 11) [47].

PPy (polypyrrole) coated GO/rGO based highly conductive ceramic membranes, worked like an electrode was prepared for wastewater treatment. There are a very small number of reports available in the literature regarding the wastewater remediation property of conductive ceramic membranes since they have very poor electrical conductivity. Under the applied electric field, it displayed excellent anti-fouling ability including improved contaminants removal efficiency as because of doping of highly reactive GO/rGO over it as it contains large surface area. Pyrrole gets excellently adsorbed on the surface of the GO/rGO as it makes a large number of non-covalent interactions like electrostatic interactions, pi-pi interactions, H-bonding, etc., rather than polymerization over the surface of the membrane which ultimately improved the membrane properties like hydrophilicity, flux, porosity, roughness, and zeta potential, etc. Due to the highly conductive network-like structure made between PPy and GO/rGO, it resulted decrease in the electrical resistivity of the membrane to 3.56 and 0.87 kΩ/cm from 8.46 kΩ/cm. under applied electric field, the average specific flux of rGO/PPy (GO/PPy) membrane was found to be 47.5% (33.6%) which was quite higher than GO/rGO membrane supported by CM at the time of yeast filtration which made it a more profitable candidate for water treatment. Derjaguin–Landau–Verwey–Overbeek (DLVO) theory proved that after incorporation of GO/rGO over PPy membrane, it improved the zeta potential, hydrophilicity, weakens the roughness which in turn boosted the formation of more positive non-covalent network formation which ultimately helped in the enhancement of the anti-fouling property of the membrane (Figs. 12, 13 and 14) [48].

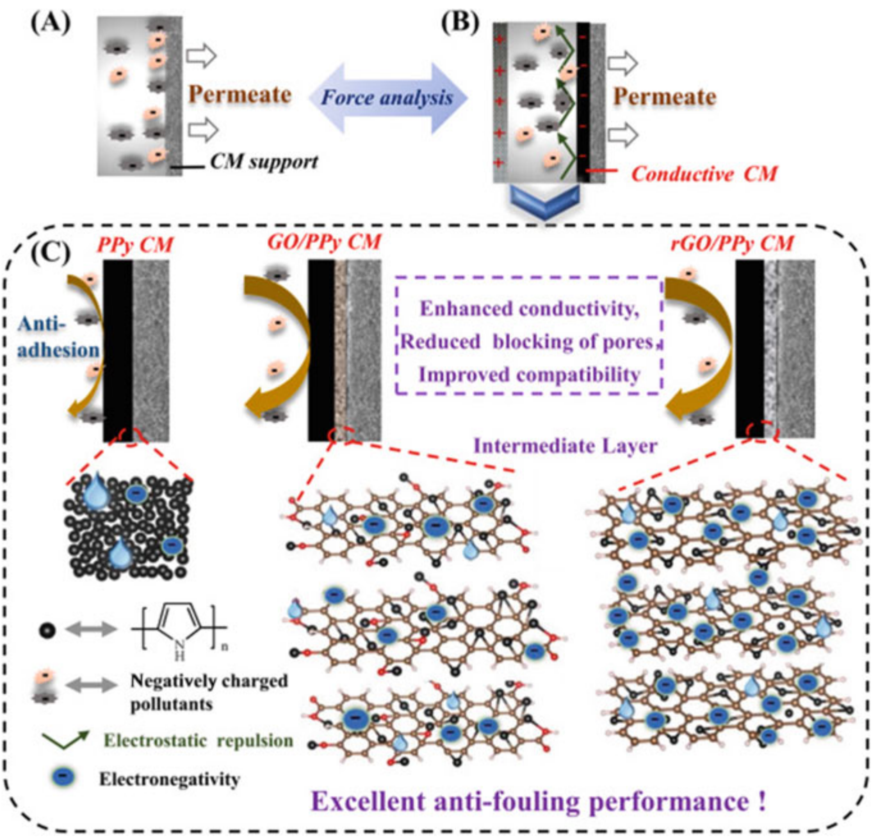

Fig. 12 The separation process of **a** Ceramic membrane (CM) support, **b** conductive membrane under electric field; and **c** the schematic diagram of the GO/rGO reinforced PPy conductive membrane. Reprinted with permission from [48]. Copyright (2022), Elsevier

Multiplex electrochemical sensors made up of covalently functionalized GO with thymine and carbohydrazide (Thymine-GO-Carbohydrazide, T-GO-C) were prepared through an epoxide ring cleavage, followed by simultaneous-reduction approach and applied for the detection of heavy metal ion in the wastewater samples. The prepared T-GO-C-based multiplex electrochemical sensor possessed admirable electrode stability and showed high selectivity toward Hg (II) and Cr (VI) at 0.27 V and 0.9 V when silver chloride (Ag/AgCl) was taken as reference electrode. The large surface area facilitated more conductivity and high functionalization displayed superior selectivity toward the detection of Cr (VI) and Hg (II) with minimum detection limit of 20 ppb and 1 ppb respectively in real water samples. Additionally, it exhibited a linear response for Cr (VI) and Hg (II) above 5 ppb and showed high accuracy, portable, good recyclability, and reusability (Fig. 15) [49].

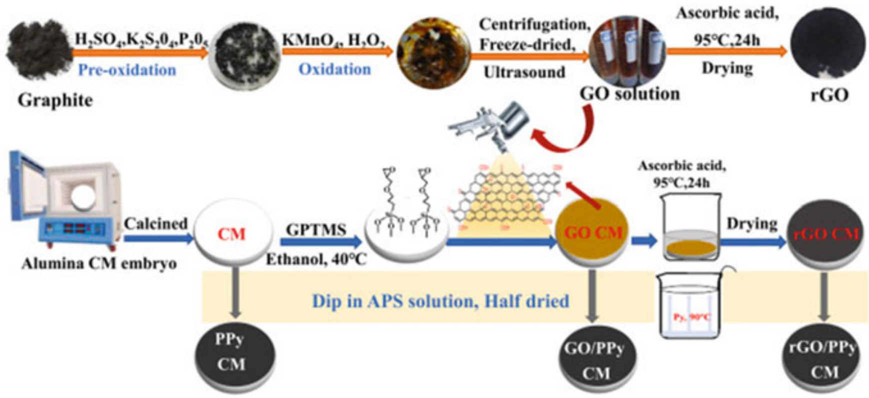

Fig. 13 Schematic diagram of the preparation process for GO, rGO, and conductive membranes. Reprinted with permission from [48]. Copyright (2022), Elsevier

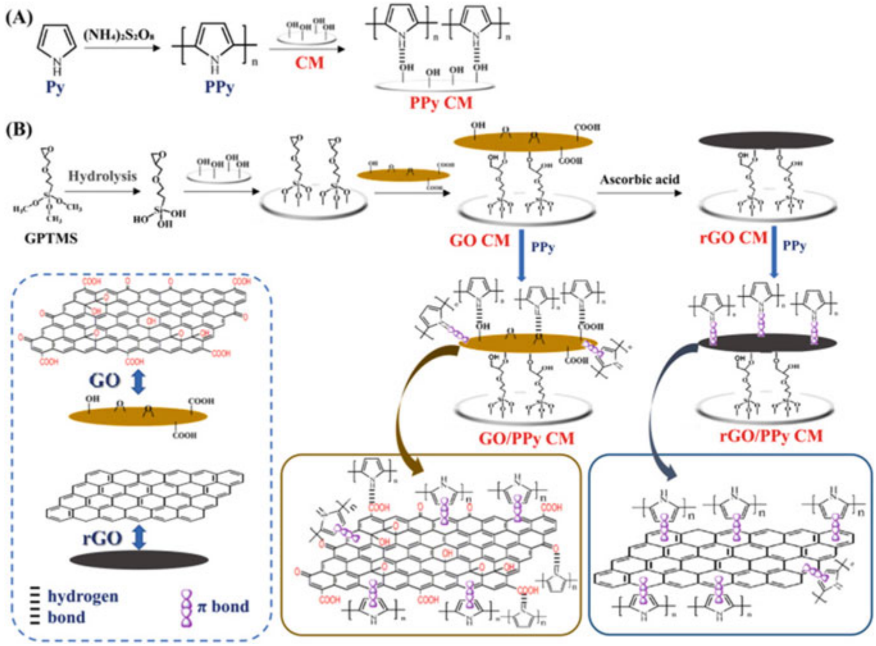

Fig. 14 Synthetic routes of **a** PPy CM, **b** GO/PPy CM, rGO/PPy CM; possible interactions of hydrogen bond and π bond existed between the PPy chain and GO; π bond existed between the PPy chain and rGO. Reprinted with permission from [48]. Copyright (2022), Elsevier

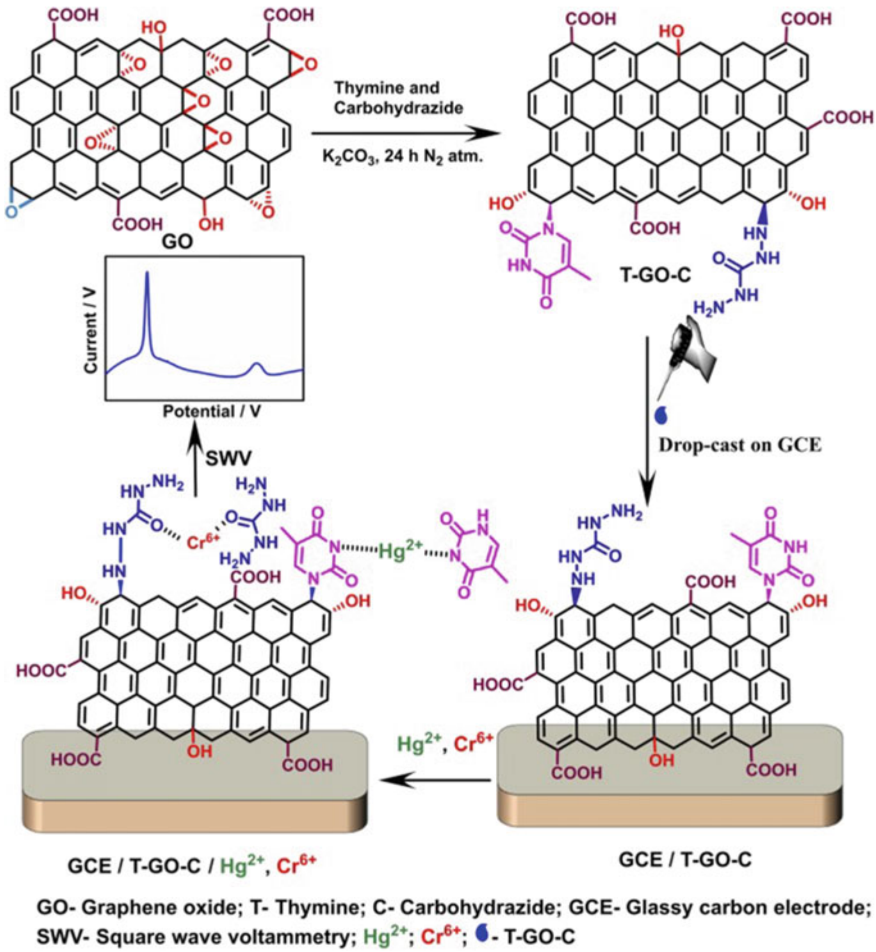

Fig. 15 Schematic representation of the T-GO-C nanomaterials fabricated electrochemical sensor electrode and its SWV sensing of Hg (II) and Cr (VI). Reprinted with permission from [49]. Copyright (2022), Elsevier

3 Conclusion

Environmental pollution is rising day by day due to the establishment of various environmental sectors which, though provide high economic strength but also create various lives threatening air, water, and soilborne diseases. Survival with the growing environmental pollution is the biggest challenge for human civilization. Nanotechnology and nanomaterials always mesmerized the scientific communities all over the world because of its multidimensional applications. Invention of graphene oxide-based nanomaterials brings bumper offers and opportunities with it to fight the increasing environmental problems. Due to the nano-range particle size with high surface area, GO and GO-based nanomaterials can be used in different forms to detect the different types of environmental contaminants. Organic pollutants, dyes, heavy metal ions, micro-organisms can make a few different kinds of interactions such as pi-pi interactions, H-bonding, cation-pi interaction, van der Waals interactions etc. with different kinds of functionalities present on the surface of the GO which in turn helps in easy detection. GO is also hydrophilic in nature which also can be recycled after multiple uses. Easy method of synthesis, avoid of toxic reagents solvents and cost-effectiveness with high yield are the major advantageous features found to be associated with the nanomaterials. Additionally, it exhibits ultra-high sensitivity and selectivity. This review will help future researchers and academicians to gain more ideas about the different methods of synthesis and applications of GO-based nanomaterials which will help them to think new and innovative protocols with different multiple novel applications.

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