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REVIEW ARTICLE

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Synthesis and applications of carbon porous nano-materials for environmental remediation

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ABSTRACT

Carbon-based porous materials are widely used as adsorbents due to their high adsorption capacity and unique properties such as large pore size, sizeable area-to-volume ratio, high thermal & electrical conductivity etc., to remove pollutant from water and thus helps in water remediation. Water contamination poses severe impacts on humans as well as on marine life. In this review, we studied porous carbon materials such as graphene, carbon nanotubes and activated carbon, including their synthesis, properties and wide applications in water remediation. Absorbent materials at different scales for these applications are auspicious for environmental remediation. This review also provides future endeavors of carbon porous materials towards sustainable techniques for an eco-friendly environment.

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1. Introduction

An increase in population, urbanization and industrial activities leads to the addition of pollutants in water directly or indirectly. The accumulation of contaminants in the water threatens humans and the environment (Karamveer et al., 2022; Siwal, et al., 2022; Tshikovhi et al., 2020). Water quality decreases daily as harmful contaminants like antibiotics, pesticides, heavy metals, dyes and volatile organic compounds are directly or indirectly flown into water bodies (Adedeji et al., 2021; Kaur et al., 2022; Sheoran et al., 2022). The concentration of these chemicals beyond the mark causes severe detrimental effects on human and aquatic life. To maintain sustainable growth, a technology efficient in detecting and eliminating these contaminants from water is needed. Carbon porous materials have a high specific area, open pore structure, and high electrical and thermal properties, making them highly feasible to use as adsorbents (Lee et al., 2006; Mishra et al., 2022; Samarjeet Singh Siwal et al., 2022; Wang et al. 2020).

Carbon-based nano-materials have been satisfactorily identified with superior implementation and tailorable effects in the adequate degradation of contaminants (Hussain et al., 2021; Kumar Mishra et al., 2021). Wherein carbon nanofibers (CNFs) have exhibited a high possibility of eradicating contaminants from water owing to their benefits of easy synthesis, chemical resilience, and economic and environmental friendliness (Kumar et al., 2022; Sudhaik et al., 2022).

In this review, we provide a detailed overview of the application of carbon porous materials in

environmental remediation with a particular focus on water remediation. The role of various carbon porous materials and their derivatives in water remediation and the future prospectus are also studied through a literature survey, including their synthesis method.

2. Classification of carbon porous materials

The porosity of any material is defined in terms of the volume percentage of air. It is calculated as the total volume occupied by the voids or space to the total volume of the material (ben Mosbah et al., 2020). In this study, we are only concerned with carbon's porous materials. Different classification has been given to carbon porous materials on another basis. The first is based on pore size, by determining the size of pores of the porous materials, which are categorized into three main categories: micropores, mesopores, and macropores (Kaur et al., 2021; Kumar et al., 2021; Mishra et al. 2022; Samarjeet Singh Siwal et al., 2021). The other carbon porous materials are graphene and its derived products, non-graphitic material, activated carbon and single or multi-walled carbon nanotubes, as described in Scheme 1. In this section, we provide information regarding the classification of carbon porous materials.

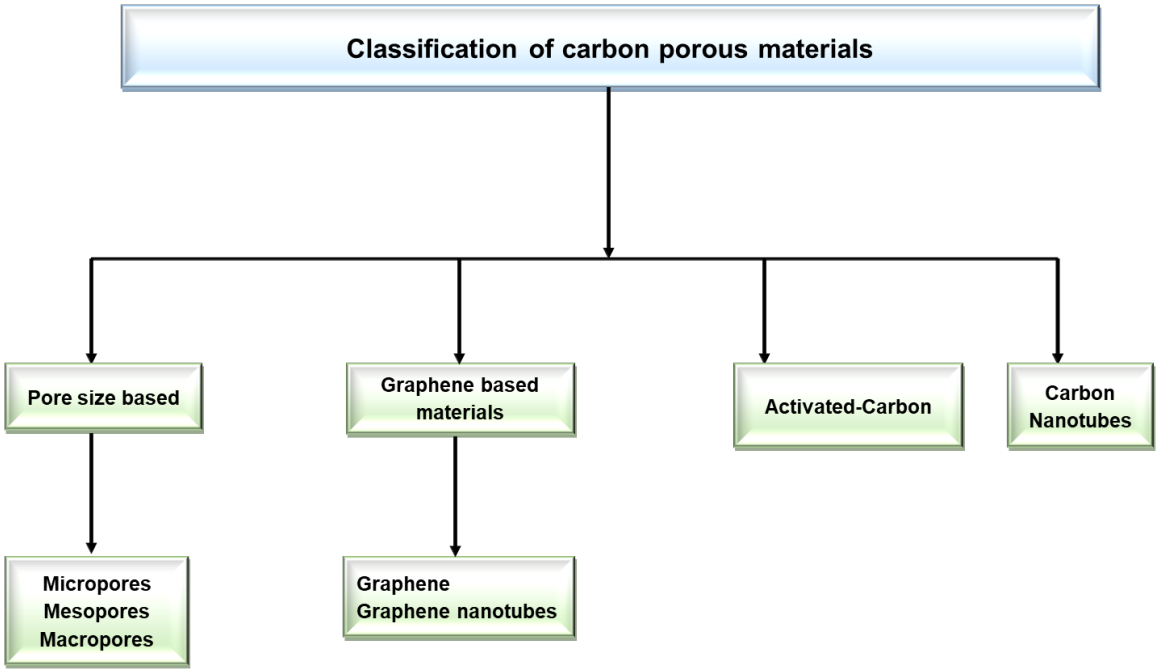
2.1. Classification based on the size of pores

Based on the size of pores, porous materials can be divided into three significant categories micro, Meso and macro-porous materials (Sun, 2019).

Micro-porous materials- Carbon porous with a highly narrow pore diameter of less than 2 nm lies in the category of microporous materials. This type of absorbent material has applications as a drying agent in the catalysis and adsorption of different materials.

Meso-porous materials- Meso-porous materials are those whose pore size diameter lies in the range of 2-50 nm. They have narrow pore sizes, high surface area, biocompatibility, and low toxicity (Sayari, 1996). Meso-porous materials are widely used in catalysis, adsorption, filtration, pollution control, nanotechnology, and electronics.

Macro-porous materials- The pore size, including a diameter above 50 nm, are considered macro-porous materials. Macro-porous materials have considerable application in eliminating pollutants, catalysis, and photodegradation (ben Mosbah, Mechi, Khiari, & Moussaoui, 2020).



Scheme 1. Classification of carbon porous materials.

2.2. Graphene-based materials

There are two types of graphene-based porous nanocarbons: graphene and graphene nanotubes.

2.2.1. Graphene

Graphene is a newly discovered carbon allotrope with large surface area, high intrinsic mobility, high thermal conductivity, and a significant value of Young's modulus (Tiwari et al., 2016). Graphene has an essential place in the field of material science. It is the mother of all graphitic carbons having applications in electrochemical sensing and energy storage devices such as supercapacitors and fuel cells (Obodo et al., 2019; Siwal et al., 2019; Siwal et al., 2020). Further, graphene has different forms, such as graphene oxide (GO) (Siwal et al., 2018), reduced graphene oxide (rGO) (Siwal et al., 2019), graphene quantum dots (GQDs) and graphene aero gels (Sheoran et al., 2022; Tiwari et al., 2020). Fig. 1 represents the structures of graphite, graphene, GO, and rGO.

2.2.2. *Graphene Nanotubes*

Graphene nanotubes are sheet-like structures made from graphene when graphene is rolled up, acquires a cylinder shape, and takes the form of a

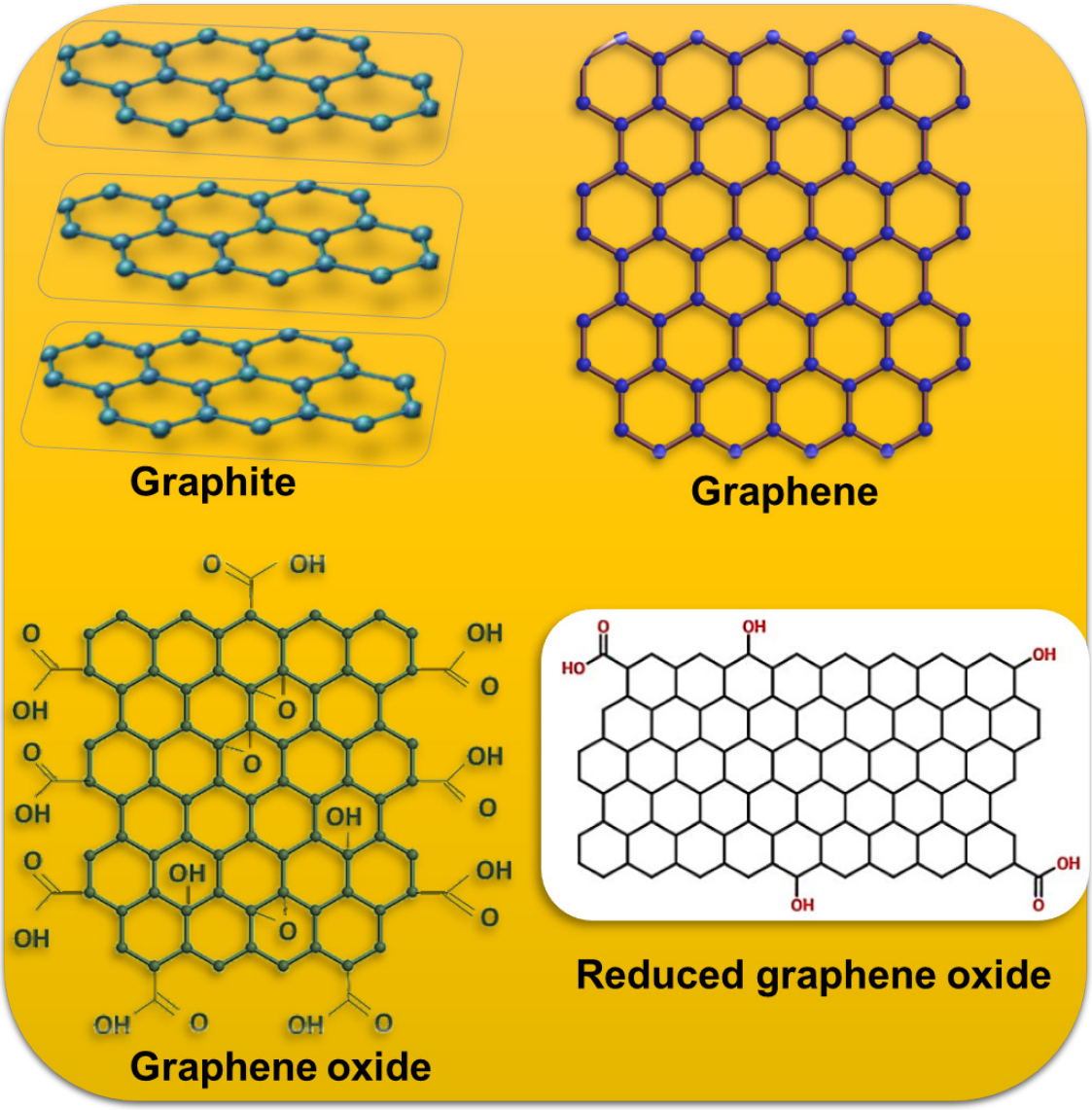


Figure 1. Structure of graphite, graphene, GO, and rGO.

tube. By unzipping them, we can move towards the original graphene. Graphene nanotubes improve surface properties and catalysis when forming a composite material. The graphene nanotubes' structure is shown in Fig. 2 (Tîlmaciu & Morris, 2015).

2.3 Activated Carbon

Activated carbon is the other name for activated charcoal. Compounds with high amounts of carbon, such as coal, coconut shell, and wood, are significant sources of activated carbon. It is

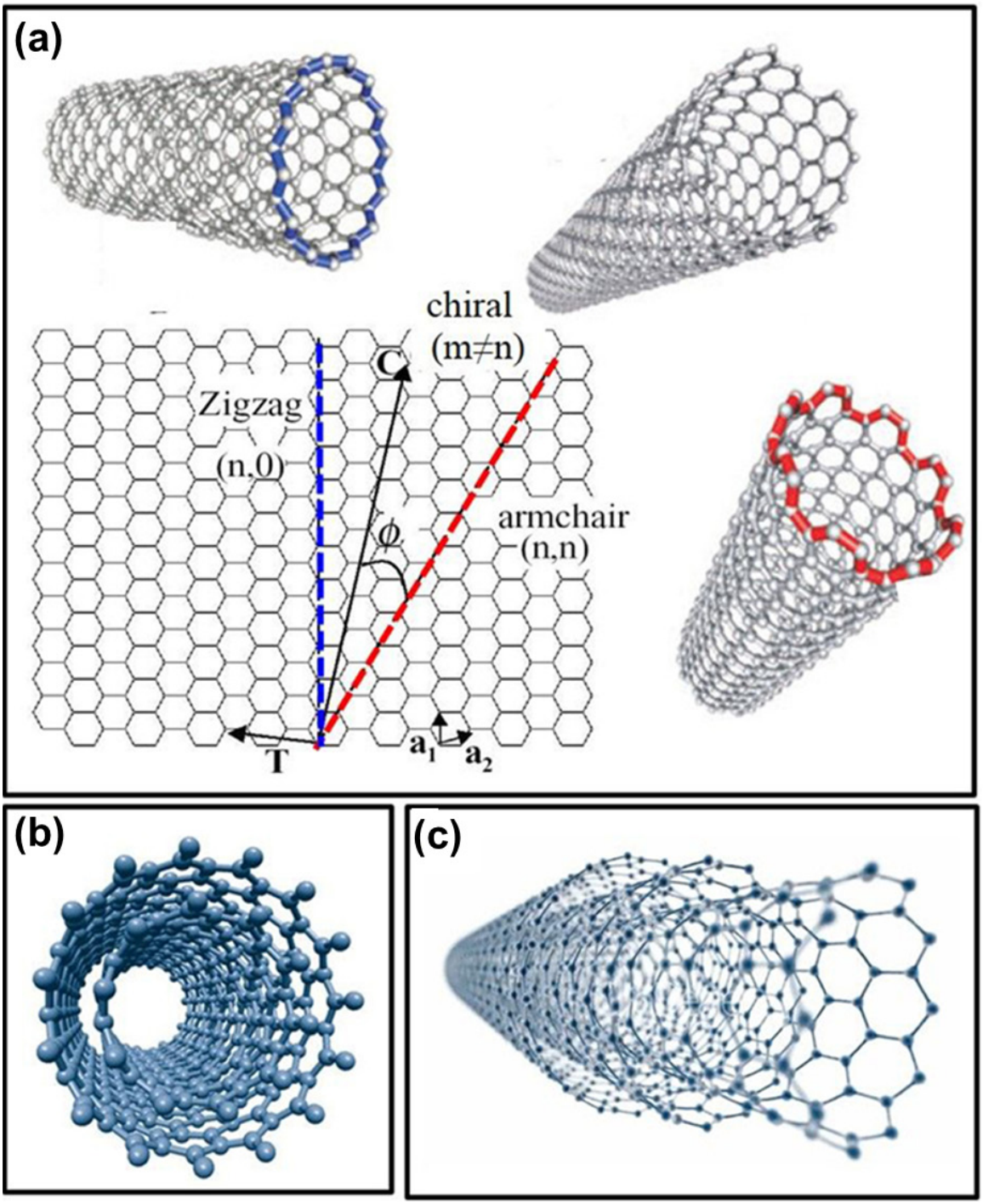


Figure 2. Structure of graphene nanotubes. Reprinted with permission from Ref. (Tîlmaciu & Morris, 2015).

the best adsorbent having a large surface area, the most potent physical adsorption forces and the adsorbing porosity with the highest volume. Activated carbon is further classified into five types based on their physical characteristics, described in the following subsection.

2.3.1. Powdered activated carbon

Powdered activated carbon has a large internal surface and a small diffusion distance. It comprises a specific powder form with a size of less than 100 nm and a diameter of 15-25 μm.

2.3.2. Granulated Activated carbon

The particle size of granulated AC is slightly larger (0.2 mm to 5 mm) than powdered activated carbon. The external surface of these AC is small, has high diffusion rates, and is thus preferably used for the adsorption of gases or vapors. They are wide applications in water remediation and separation of components etc. They can be regenerated and thus reused also.

2.3.3. Spherical activated carbon

Spherical activated carbons are spherical balls with tiny particle sizes, a high absorptivity towards SO_2 and NO_2 and excellent mechanical strength. They are widely used in solvent recovery, filter gas treatment, water purification by adsorption, etc. (Manocha, 2003).

2.3.4. Impregnated carbon

When activated carbon is further impregnated with certain chemicals such as iodine, silver and cation of Al, Zn etc., to enhance its properties, and used impregnated activated carbon is with silver for water purification.

2.3.5. Polymers-coated Activated carbon

Polymer-coated activated carbon is the one in which a biocompatible smooth coat is placed on the activated carbon so that the coat should not block pores. The application of polymer-coated activated carbon is in Hemoperfusion. Gazzard *et al*. (1974) studied the polymer coating of activated carbon and how it affects the bio-compatibility and binding of paracetamol. Hemoperfusion is a blood purification technique in which the patient blood is passed through an adsorbent extra-corporeally, and the adsorbent absorbs toxic material into the blood.

Activated carbon contains three types of pores in its structure which affect the performance of the activated carbon as an adsorbent.

2.4. Carbon nanotube

A sp^2 hybridized carbon allotrope with the proper application as an adsorbent in the form of rolled graphene sheet is known as a carbon nanotube. Japanese physicist Lijima and coworkers came up with a revolutionary change in materials science after discovering CNTs in 1991 (Kaur et al., 2019). CNT's outstanding properties include

- Mechanical, high thermal conductivity,
- Chemical stability,
- A significant value of tensile strength and high electrical conductivity,
- Making it an extraordinary material suitable for various applications.

CNT has a hollow inner part responsible for the uniqueness of CNTs among all allotropes of carbon. It can be manipulated either physically or chemically to enhance its properties further. Based on the no. of concentric cylinders, CNT has been classified into two categories; single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) (Gupta et al., 2019). The comparison of different characteristics of SWCNTs and MWCNTs is shown in Table 1 (Rudakiya et al., 2019; Saifuddin et al., 2013).

2.5. Carbon porous gels

Porous amorphous carbon materials derived from organic gels are called permeable or carbon aerogels. The process used to convert organic gels into carbon aerogels is named carbonization or pyrolysis at very high temperatures (Faruk & Sain, 2015). They are electrically conductive and chemically inert materials having low density and a very high surface area. Therefore, they are widely applied in environmental chemistry for removing pollutants like oils, toxic organic solvents, dyes, heavy metal ions in aquatic

Sr. No.	SWCNTs	MWCNTs
1.	It is formed only with a single layer of graphene	It is formed when a no. of graphene layer rolled up in the form of a cylinder
2.	While synthesizing SWCNTs catalyst is required	It can be synthesized directly without using a catalyst
3.	The chance of defect is more during functionalization	The chance of defect is less especially when synthesized by the arc-discharged method
4.	Synthesis in bulk is challenging	Bulky synthesis is easy
5.	Twisting of SWCNT is easy	Twisting of MWCNTs is not easy
6.	Characterization and evaluation are easy	Characterization and evaluation is not so easy
7.	A less pure form of CNT	It is highly pure CNT

Table 1. Comparison table between SWCNT and MWCNT.

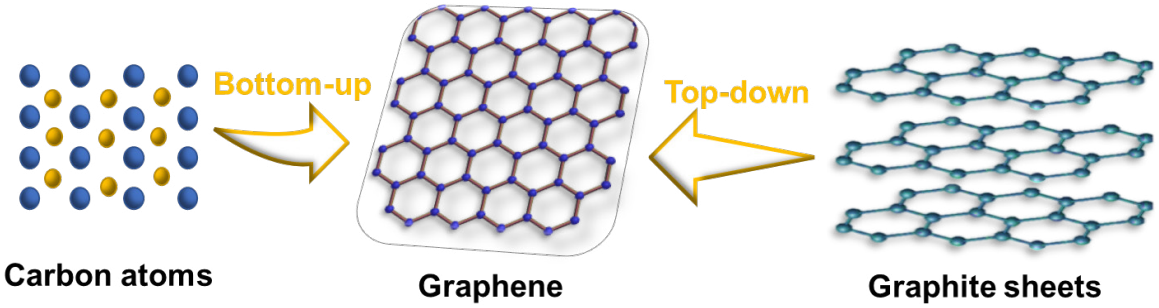


Figure 3. Diagrammatic representation of top-down and bottom-up approaches of graphene.

environments, and volatile organic compounds (VOCs), carbon oxides (CO_2, CO), nitrogen oxide (NO), and hydrogen sulfide (H_2S) in the atmosphere (Gan et al., 2019). They can be used as energy storage materials, a suitable catalyst supporter and adsorbents.

3. Synthesis of carbon porous materials

3.1. Synthesis of graphene

Graphene has an essential place in the category of carbon-porous materials. Due to its remarkable properties, graphene draws the attention of researchers to itself. There are several methods to synthesize graphene. The top-bottom and bottom-up approaches are the two main methods, as shown in Fig. 3. Graphite comprises graphene layers held together by Vander Waal forces of attraction; graphene can be produced from graphite by reducing this force of attraction and simultaneously enhancing the interlayer distance. The top and bottom approach involves breaking graphite into graphene. Graphite comprises parallel graphene sheets held together by Vander Waal forces. By separating these stacked sheets by various means, graphene can be made. But it is a challenging task to do. There are several challenges included in this method, like the deformation of the surface while separating the sheets.

Consequently, the major drawbacks are a low yield and the number of steps involved in the procedure (Edwards & Coleman, 2013). A bottom-up approach involved carbon obtained from alternative sources as the basic unit of graphene (Shams et al., 2015). This approach is suitable for carbon nanoribbons, carbon dots and carbon films by carbon growth on a specific substrate (Warner et al., 2012).

3.1.1. Top-down methods

The top-down approach involves the reduction or exfoliation of powdered graphite, where mechanical and electrochemical peelings are mainly used (Kumar et al., 2021).

3.1.1.1. Mechanical exfoliation

Mechanical exfoliation was the very first method discovered for the synthesis of graphene. It is a straightforward process and yields high-quality

graphene with almost no defects. Mechanical exfoliation involved peeling off the graphite sheets and cleaving them into several graphene flake layers. Two types of forces can be worked: normal force and sheer force. Peeling can be done using adhesive tape, an electric field, ultrasonication etc. Peeling off the graphite is known as micromechanical cleavage (Demon et al., 2020; Novoselov et al., 2004).

Micromechanical cleavage of highly ordered pyrolytic graphite is associated with the emergence of the first graphene flake. The basic idea behind this is that the scotch tape exerts a normal force sufficient to overcome the Vander Waal forces in graphite. The bits of graphite that adhere to the tape are cleaved preferentially along the plane of the crystal, leaving the exposed atomically flat surface. To obtain few and single-layer graphene, the clean tape is pressed against the graphite flakes adhering to the first piece of tape. Peeling apart these two pieces of tape further cleaves the graphite into even thinner flakes. This process is repeated as often as desired, with each alteration producing thinner sheets of the graph (Whitener & Sheehan, 2014). The graphite layer becomes thin every time; ultimately, a single-layer graphene is obtained.

3.1.1.2. Electrochemical exfoliation

The electrochemical exfoliation method is a crucial environment-friendly method of producing pristine graphene, graphene oxide, heteroatom-doped graphene, etc., which is systematically represented in Fig. 4 (Liu et al., 2019) and requires less processing time. This method uses graphite as one of the electrodes in the natural form of graphite foil, graphite powder, rods or sheets or highly oriented pyrolytic graphite (2015). A particular potential was applied to intercalate the ions into graphene sheets and form gaseous species, which on expanding, enhances the interlayer distance between the sheets, as shown in Scheme 2. This ion intercalation is affected by several factors, such as defects in graphite, graphite particulate size, and thickness. Parvez *et al*. (2013) stated the effect of the concentration of electrolyte on exfoliation efficiency by using sulfuric acid as an electrolyte and a +10 V voltage for 2 mins and concluded that a lower concentration of 0.01M electrolyte has more exfoliation efficiency than the electrolyte having a concentration between 1M to 5M. The reason behind that is the generation of extra fragmentation of graphite by high-concentration electrolytes. Fuertes Sevilla *et al*. (2016) stated in their study that the thickness of graphite affects the exfoliation rate of graphite; thick graphite sheets are exfoliated slower than thin ones. Munuera *et al*. (2015) stated that structural imperfection, such as deformation, wrinkles, voids etc., in the graphite foil enhances the rate of exfoliation of graphite and produces better quality one-to-two-layer graphene. A summary of graphene synthesis using electrochemical exfoliation is shown in Table 2.

3.2. Synthesis of carbon nanotubes

The most widely used methods for the fabrication of CNTs are electric arc discharge (Shi et al., 2000), laser ablation (Chrzanowska et al., 2015) and chemical vapour deposition method (2003).

3.2.1. Electric arc discharge method

This method is based on the principle that in an inert environment or liquid medium, graphite's arc sublimation results in CNT accumulating on one of the electrodes when cool down (Hernandez et al., 2008). In this method, a chamber filled with inert gas is used in which two electrodes of graphite are placed at a short distance (1-4 mm) apart at reduced pressures ranging from 50 to 700 mbar. The diameter of the graphite electrodes is measured as 6-12 mm. Then a direct current of 50-120 A under a potential of around 30 V is passed through the electrodes, which generates high-temperature plasma between two electrodes; as the current is passed, carbon atom starts removing out from the positive electrode anode and consequently, the anode starts decreasing in its length simultaneously generation of CNT starts at the cathode. Carbon is removed from the anode and forms small clusters of carbon; after rearranging themselves, these clusters take out the form of a tube and reach the anode as MWCNT. The formation of undesired graphite from the carbon atoms vaporized from the anode restricts the formation of MWCNT (Dervishi et al., 2009).

For producing a high-quality and good yield product, a very high reaction temperature of 3000^{o} C is preferable with highly thick graphite rods in a mighty arc reactor (Yan et al., 2015). Yousef *et al*. (2013) used de-ionized water with

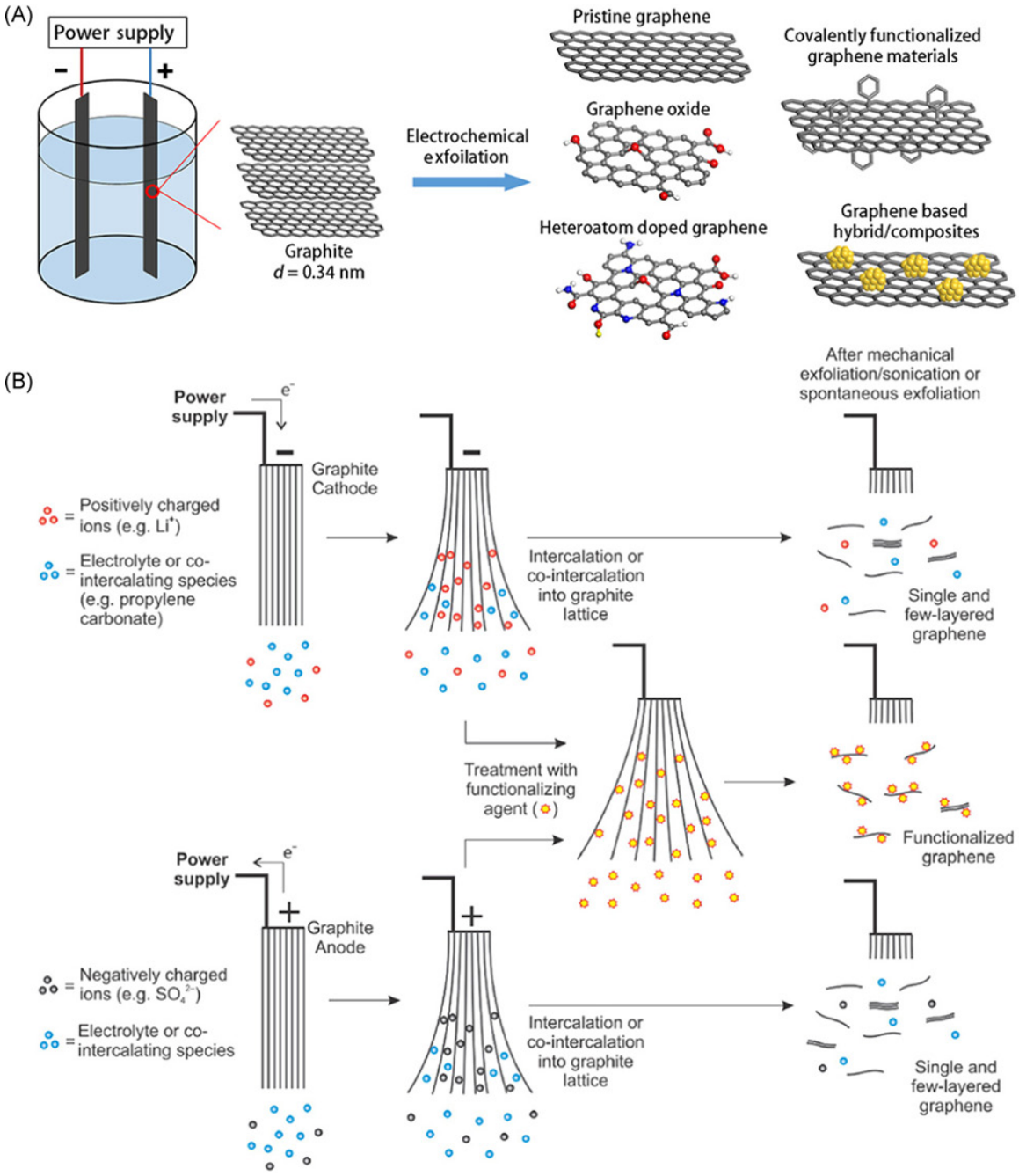
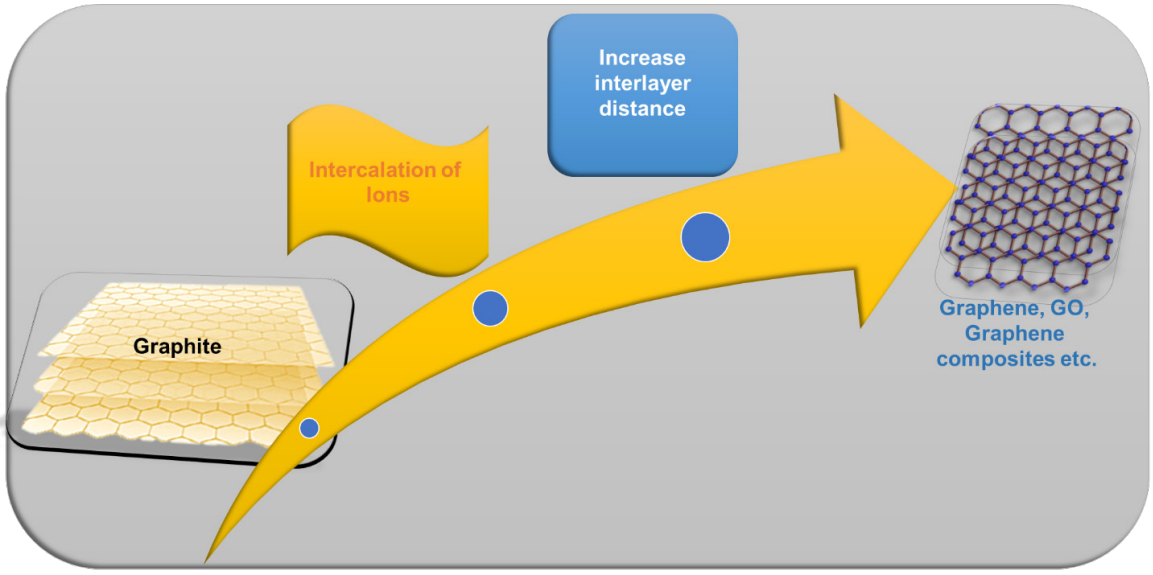


Figure 4. A systematic diagram of the electrochemical exfoliation method of graphene synthesis. It is reprinted with permission from Ref. (Liu et al., 2019).

extra pure (99.9%) graphite electrodes to produce MWCNT using the arc discharge method. The product yield in the case of multi-plasma electrodes exceeds 320% more than in the case of single-plasma electrodes. Sagara *et al*. (2014) synthesized a metal-filled carbon nanotube using an arc discharge method in a liquid ethanol medium.

3.2.2. Laser ablation method

The second critical approach to producing CNTs is laser ablation. This method is based on the same principle as the electric discharge method (Dervishi et al., 2009). A laser source completes the high-temperature requirement between the graphite electrodes. As a laser beam is irradiated



Scheme 2. Graphene synthesis by suitable intercalating ions into graphite.

Sr. No.	Precursors	Electrolyte used	Applied potential	Product	Type of graphene	Ref.
1.	Graphite	H_2SO_4, H_3PO_4, $(NH_4)_2SO_4$	10V	Graphene	Multilayer	(Htwe, Chow, Suda, Thant, & Mariatti, 2019)
2.	Graphite	Na_2SO_4	2-10V	MoS_2/Graphene	Monolayer and multilayer	(Ali, Thalji, Soh, Algarni, & Chong, 2020)
3.	Graphite foil	$(NH_4)_2SO_4$, $(NH_4)_2HPO_4$	+10V	Graphene	Multilayer	(Sharif et al., 2020)
4.	Graphite foil	$(NH_4)_2SO_4$(aq) + TEMPO	+10V	Graphene	Two-layer graphene	(X. Zhao et al., 2020)
5.	Graphite rod	$(NH_4)_2SO_4$	+10V	Graphene	Graphene	(Miao et al., 2016)

Table 2. Synthesis of graphene by electrochemical exfoliation method.

on one of the graphite electrodes, graphite is vaporized in the presence of some inert gases, and the carbon atom starts removing from the anode. CNT starts generating at the anode on cooling (Yan et al., 2015). A very high temperature, highly pure graphite rods and reduced pressure are required for the sublimation of the electrode. Justyna *et al*. researched the effect of laser wavelength on the production yield of SWCNT by using the laser ablation method and studied the properties of SWCNT (Chrzanowska et al., 2015).

3.2.3. Chemical vapor deposition

This is a commercial-based method that involves the decomposition of carbon-containing compounds. The chemical vapor deposition method works at low temperatures compared to the above methods. A hydrocarbon source is placed in a quartz tube filled with inert gases under a high temperature of around 700-1000° C in the presence of a catalyst such as Fe, Co, Ni etc. The hydrocarbon source is generally a gaseous molecule of CH_4, CO or C_2H_2 (Chrzanowska et al., 2015), which decomposes into carbon and hydrogen on heating at high temperatures. These carbon atoms rearrange themselves into a structure of CNTs and finally precipitate out. The hydrocarbon source can be liquid or solid, benzene, alcohol or naphthalene (Dervishi et al., 2009). Kumar *et al*. (2018) prepared MWCNT using a thermally catalytic vapor deposition method using acetylene as a hydrocarbon source and Fe/MgO as a catalyst (Arunkumar et al., 2020).

3.3. Synthesis of activated carbon

Activated carbon can be easily prepared from biomass having a high carbon content, such as bamboo, coconut husk, willow peat, wood, coir, lignite, coal, petroleum pitch, almond husk, nutshell etc., either directly by activation or by some indirect processes as represented in Fig. 5. Physical activation, chemical activation and physiochemical activation are the most widely used methods for the preparation of this porous carbon material.

The physical activation process comprises two steps carbonization followed by the activation of raw precursors. The carbonization step involves the pyrolysis of the raw precursors at high temperatures in inert conditions (Odetoye et al., 2019). Firstly, thermal degradation of the carbonaceous material is to be done to avoid any volatile material in contact with it and enhance its pure carbon content. The resultant product of the carbonization process is named the bio-char having a low surface area which was unsuitable for high adsorption. The specific surface area can be enhanced by further activating the biochar produced (Rashidi & Yusup, 2017). The optimal temperature range for the carbonization process is 400-850^{o} C. Activation of the carbonized product is done in the presence of some oxidizing agent such as CO_2, air, steam or its mixture with air (Braghiroli et al., 2020). Another method for preparing activated carbon is physiochemical activation, combining physical and chemical activation. This method includes chemical activation followed by an additional physical activation step.

4. Application of Carbon porous materials in water remediation

Water quality is the primary concern in the modern era. Identifying the contaminants and preventing water from these contaminants is a crucial step to ensure the quality of water. Carbon porous materials can solve the problem even at the nano-scale due to their high surface area, non-poisonous nature and biodegradability (Baby et al., 2019; Chaudhary et al., 2021; Samarjeet Singh Siwal et al., 2021). Significant contaminant that pollutes water is organic pollutants, heavy metal ions, and different pharmaceuticals, which cause substantial risk to human health (Aigbe & Osibote, 2021; Kaur et al., 2022). Heavy metals have detrimental effects on human health, such as improper functioning of the heart, brain and kidneys (Singh et al., 2011). Therefore, their removal from drinking water is essential.

4.1. Removal of heavy metals and organic pollutants

Maintaining an accurate level of heavy metals and organic compounds in water is necessary due to their toxicity and carcinogenicity, which pose a threat to aquatic and human life (Bassyouni et al., 2019). Many techniques have been used till now to remove heavy metals by using carbon porous materials like graphene and its oxides, carbon nanotubes, activated carbon and other carbon materials. The most commonly found heavy metals in wastewater include arsenic, cadmium, chromium, copper, lead, nickel, and zinc (Jaishankar et al., 2014; Kaur et al. 2022) and their sources are illustrated in Fig. 6. Organic

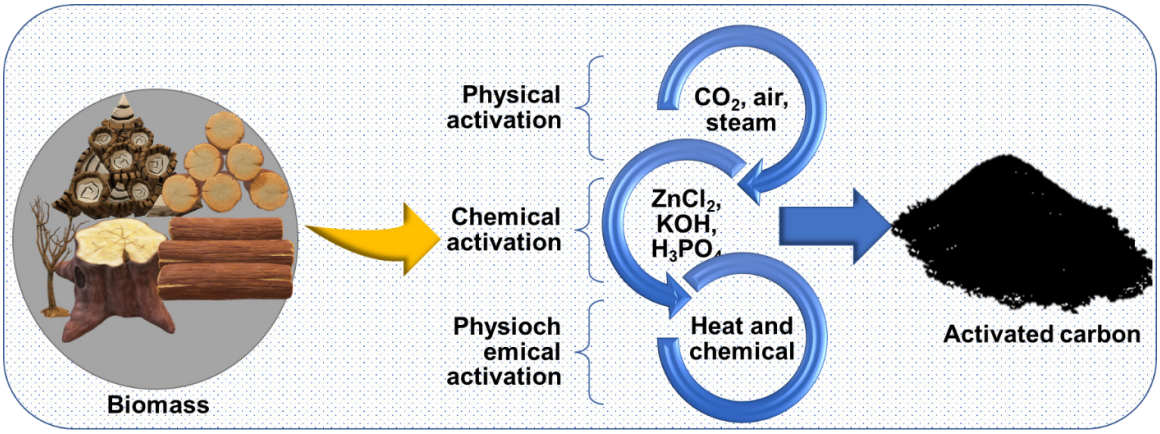


Figure 5. A diagrammatic view for activated carbon synthesis from biomass.

pollutants include dyes, pesticides like DDT, and nitro-phenols (Ali et al., 2012; Mandeep et al., 2020).

GO is said to be a promising adsorbent as it forms metallic ion complexation. Several studies state the application of graphene as an effective adsorbent for removing metallic ions from water (2011). GO, and rGO is better adsorbents than pristine graphene. The reason is that GO has high oxygen group content interacting with metal ions (Lee & Yang, 2012; G. Zhao et al., 2011). CNTs are also used to eliminate heavy metals from water sources, and the adsorption capacity of CNTs can be easily improved by functionalizing them with some organic molecules (Gupta, Agarwal, & Saleh, 2011). Furthermore, AC is utilized to study the adsorption of Cu(II) ions onto spent activated clay, a waste produced from an edible oil refinery. The study states that the adsorption Of Cu(II) on low-cost AC adsorbent is a spontaneous process determined by the specific surface interaction mechanism (Weng, Tsai, Chu, & Sharma, 2007).

Dyes are widely used in textiles, cosmetics, paper printing etc. The waste from these industries, without any proper treatment, is quickly dumped into the water. Several studies have been done; for instance, Robati *et al*. (2016) studied the usage of GO to remove two dyes, methyl-orange (MO) and basic red 12 (BR12), from an aqueous solution with a maximum removal efficiency of 16.83 mg/g for MO and 63.69 mg/g for BR12 at pH value 3 of the aqueous solution. Banerjee *et al*. (2015) examined the effectiveness of GO nanoplatelets in the adsorption of the azo dye present in wastewater. It reported a 97.78% removal of safranine dye at the end of the experiment. The study of these researchers is described in Table 3.

4.2. Removal of pharmaceuticals

Pharmaceuticals are drugs or medicines which are used as a remedy to prevent disease. The presence of these elements in surface and groundwater is the hotspot case of study due to the harmful effect of these chemicals on the environment. Including

Figure 6. Different sources of heavy metal ions.

Sr. No.	Adsorbate	Adsorbent	Optimized time	pH of an aqueous solution	Maximum efficiency	Initial concentration	Ref.
1	a) Methyl orange b) BR12	GO	100 min	3	a) MO =16.83 mg/g b) BR12= 63.69 mg/g	0.2 mg/mol	(Robati et al., 2016)
2	Safranine dye	GO	45-60min	6	97.78%	-	(Banerjee, Sau, Das, & Mukhopadhayay, 2015)

Table 3. Summary of the removal of organic pollutants from water using carbon porous materials.

human and marine life, and hence the removal of these contaminants from water becomes a critical task. Pharmaceuticals are discharged into the water in several ways from the human body. They are excreted with urine, waste from pharma industries is directly discharged into water bodies, treated sewage effluent is released into water from sewage treatment plants etc. (Kookana et al., 2014). The adverse effect of these chemicals includes the potential for carcinogenicity, toxicity, mutagenicity and evolution of resistant bacteria. These pharmaceuticals include antibiotics like tetracycline, sulfonamide, and active pharmaceutical ingredients like ibuprofen, diclofenac, sulfamethoxazole, etc. Several methods are being used for the removal of these contaminants, like chlorination, electrochemical treatment (Hirose et al., 2005), membrane filtration (Rosman et al., 2018), adsorption (Yu et al., 2015) etc. and the study adsorption is the highly effective and low-cost approach (Putra et al., 2009).

Diclofenac is widely used as a non-steroidal drug to prevent inflammation and pain in the case of several sicknesses, flu-like migraine, fevers, joint pain, etc. A part of active diclofenac is excreted with urine and released in surroundings directly or by incomplete treatment by sewage treatment plants (Acuña et al., 2015). The adsorptive removal of diclofenac by GO, and the obtained maximum adsorption was 653.91mg/g (Hiew et al., 2019). Mondal *et al*. (2015) used agricultural waste to produce low-cost AC to remove ranitidine hydrochloride from synthetic water. Shan *et al*. (2016) utilized CNT-based material for the effective removal of carbamazepine (CBZ), tetracycline (TC) and diclofenac sodium (DS) from water. The maximum adsorption capacity was 369.5 µmol/g for CBZ, 284.2 µmol/g for TC and 203.1 µ mol/g for DS. Regeneration of the adsorbent was done by heating at 400 °C, keeping in mind the stability of CNT and energy saving.

4.3. Removal of dyes

Dyes can become severe pollutants when not handled or disposed of properly. Dyes can be found in wastewater streams from several industries, such as plastic, paint, textile, cosmetics, food etc. (Sangon et al., 2018). Synthetic dyes are generally poisonous and enter the food chain via water bodies. Dyes have detrimental effects on human life. They can cause skin allergies, human mutations and even carcinogenic (Brookstein, 2009) and are dangerous for the aquatic environment by deteriorating water quality. Almost 15% of dye content is lost in the dying process, which ultimately contaminates water sources; therefore, eliminating dyes is a significant issue worldwide (Khurana et al., 2017). Araújo *et al*. (2020) treated the textile wastewater using GO-based material, which acts as an adsorbent to remove methylene blue. The mechanism of removal of methylene blue from textile wastewater is showcased in Fig. 7. The authors observed a removal efficiency of 76% for methylene blue in less than one hour.

GO/silica/SWCNT nanocomposite was synthesized to effectively remove Congo red from wastewater. The composite was fabricated via the hydrothermal method and exhibited an adsorption capacity of 456.15 mg/g in approximately 5 hours (Almoisheer et al., 2019). MWCNT with a specific surface area of 181.99 m^2/g was synthesized by chemical vapour deposition to remove Ismate violet 2R dye from contaminated water. The obtained adsorption results agreed with Freundlich and Langmuir's isotherms and achieved a maximum adsorption capacity of 76.92 mg/g. It reached a removal efficiency of 88.2% at pH 4, and after 3 cycles, 91.71% regeneration was observed by the authors (Abualnaja et al., 2021).

The study of various carbon porous materials in removing pharmaceutical contaminants is summarized in Table 4.

5. Conclusion and future prospects

Porous materials with excellent adsorption and photocatalysis property show great potential in environmental remediation and energy generation. Some adsorbents, especially carbon-based materials (e.g., activated carbon, carbon nanotube, and graphene), can enhance the adsorption activity by facilitating the adsorption due to enhanced pore size and structure. Carbon porous materials have a rich porous structure high specific surface area which makes them an excellent adsorbent to remove contaminants from water. They retain structural stability during the processes of water remediation. They have reproduced in their original form post-water treatment and can be used for several cycles. The

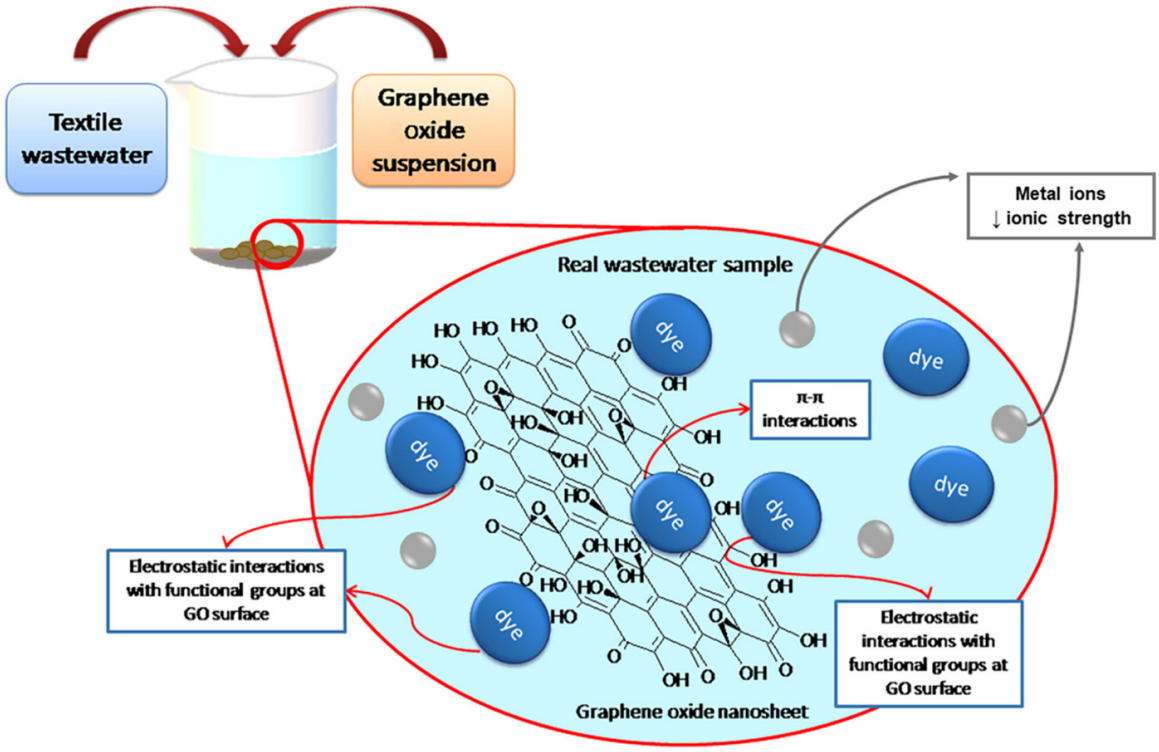


Figure 7. Schematic diagram showing the mechanism of dye removal from textile wastewater by utilization of GO. It is reprinted with permission from Ref. (de Araújo et al., 2020).

application of these bulky porous architectures in water treatment greatly depends on their surface properties and microstructure, such as the spacing size among graphene sheets and their orientation.

Their surface chemistry is considerably more leisurely to use, and the preface of preferred active groups upon the surface would be readily accomplished, rendering these substances even more helpful for the selective adsorption of any specific contaminant within the water. Most inorganic/organic pollutants have acidity or basicity in an aqueous media. This challenge is addressable by utilizing the nanoporous carbons (NCs), as they could quickly impart their surface acidic or basic nature for selectively reducing contaminants depending upon solution pH. The recyclability of the spent NCs is another factor that offers an additional advantage as it could quickly recover these materials after adsorption by employing solvent washing. Because of the benefits mentioned above, NCs and their active by-products would readily be simulated at a low cost for large-scale reduction of inorganic/organic pollutants in various industrial scaffolds.

Industrial applications require bulk production of carbon porous materials and, therefore, should develop various environmentally friendly and economically viable processes to magnify the output commercially. This also includes the preparation of the precursor, as it requires a lot of costly resources. This, in turn, will help to develop less expensive methods for quality wastewater treatment. The applications of these carbon porous materials are still limited to simple separation, such as oil and water separation, dye and heavy metal removals, and simple adsorption. Applications in the degradation and complete elimination of emerging contaminants, such as pharmaceuticals and personal care products and disinfections, are still relatively scarce. Most current studies are only based on laboratory-scale models to evaluate the performance of these macrostructures. With the advancement in technology and the improvement in research, the sector should drive carbon porous materials applications to advanced levels, such as pilot and full scale, which will benefit industrial applications. This will thereby aid in developing novel wastewater remediation techniques at the commercial level.

Type of carbon porous materials as adsorbent	Adsorbate or pollutant	Sample type	Adsorption capacity	Reaction parameters	Ref.
GO nanoplatelets	Ibuprofen (IBP)	Aqueous solution	98.17% of removal done	pH = 6 agitation speed = 180 RPM Temp. = 308K treatment period = 60 minutes	(Banerjee, Das, Zaman, & Das, 2016)
GO	dichlofenac		653.91 mg /g	pH 6 Temp. 40^{o} c contact time = 14.75 min initial conc 400 mg/L	(Hiew et al., 2019)
AC	amoxicillin	ultrapure	57.0–67.7 mg/g 93% removal done	pH = 3.2-3.6 Temp. = 293-298K initial conc. = 12.5-100mg/L contact time = 0-7000 min	(Limousy, Ghouma, Ouederni, & Jeguirim, 2017)
AC	Ranitidine hydrochloride	Synthetic water	99.16% removal	pH = 2-12 temp = 298-318K Initial cocn. = 100m mg/L Agitation speed 40-120 rpm	(Mondal, Sinha, Aikat, & Halder, 2015)
Alkali activated grapheme (G-KOH)	Ciprofloxacin	Synthetic water	~194.6 mg/g	pH = 6-8 temp = 298K initial conc. = 150 mg/L Contact time = 10min-80 min	(Yu, Ma, & Bi, 2015)
Granular CNT	Carbamazepine (CBZ) tetracycline (TC) dichlofenac sodium (DS)	ultrapure	369.5 µmol/g for CBZ, 284.2 l µmol/g for TC and 203.1 µmol/g for DS	pH = 6 Temp. = 25^{o} C initial conc. = 5-60 mg/L contact time = 72	(Shan et al., 2016)
MWCNT	resorcinol	-	-	pH = 4-8 initial conc. = 0.05 to 0.5 mg/mL	(Liao, Sun, & Gao, 2008)
MWCNT	Caffeine dichlofenac	Synthetic water	-	pH = 7 Temp. = 25^{o} C initial conc. = varies from 5-15 mg/dm^{3} Contact time = 30 min	(Gil, Santamaría, & Korili, 2018)

Table 4. Removal of antibiotics from water using carbon porous materials.

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