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REVIEW ARTICLE

Exploring the Potential of Carbon Based Materials in Air Purification

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ABSTRACT: The deteriorating air quality possessed serious health concerns among human beings and displayed damaging impact on our ecosystem. Thus converting adverse atmospheric particulate materials to high valued carbon based nanomaterials (CBNs) with photocatalytic properties in air purification has gained significant interest among researchers. This review highlights the different methodological aspects of transforming waste atmospheric particulates into useful CBNs. The review begins with a special emphasis on the synthesis and mode of action of CDs on air pollutants such as volatile organic compounds, particulate matter and many toxic gases. Various mode of synthesis of CBNs along with mechanisms used for air purification such as adsorption has also been explored in this review. The synergistic effects of combining CBNs with other materials such as TiO_2 and graphene have also explored. The feasibility of prepared CBNs in air purification processes involving the photocatalytic conversion of toxic air particulates have also been discussed in this review. The current study also highlights the sensory performance of CBNs. This exclusive study will surely assist a new opportunity in mitigating the issues related to air pollution and will improve the efficacy in environmental remediation activities for a clean and safe ecosystem.

Keywords: Air purification, Carbon based materials, Volatile organic compounds, Soot

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1. INTRODUCTION

Modern civilization and rapid industrialization have remarkably led to develop various environmental issues. As the modernization increases, it also leads to increase in several environmental crisis such as water pollution, soil degradation, waste management crisis, air pollution [1-2] and many more that significantly effects our ecosystem and human health thus, destabilizing the normal life of the planet. In particular, air pollution is one of the major challenges and a pressing environmental issue causing global concerns [3]. Air pollution refers to the presence of any harmful substances present in the air that we breathe, it can be in the form of gases, particulate materials or biological molecules. The most common air pollutants include a mixture of particles which are found in air are considered as the major contributors for the air pollution [4-8].

They are categorized on the basis of its size from 2.5 to 10 μm written as $PM_{2.5}$ to PM_{10}. The fine PMs exhibit size of less than 2.5 μm whereas the coarse particles exhibit diameter of more than 2.5 μm [9-11]. The size of pollutant particles is directly related to the expansion of the lungs and heart diseases. Smaller size particulates can easily probe into the lungs causing more detrimental effects on human health [12-14]. Depending upon the size and level of exposure, these particulates can cause mild to severe diseases [15-16]. According to the World Health Organization (WHO) report, the death rate is increasing globally year by year due to ambient air pollution and increase in global warming [17-19].

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1.1. Different sources of Air pollution and damaging impact

There are numerous potential sources for producing air pollution. Depending upon their origin and nature, they can be categorized as natural sources, man-made sources, stationary and mobile sources [20-21]. Natural sources include volcanic eruptions, thunderbolts, forest fires, radioactive decays, vegetation and ozone formation at ground level. Volcanic eruptions generate a significant amount of gases and PMs such as SO_2 and ash into the atmosphere [22]. Thunderbolts produces NOx [23], wind erosion that emits crystal dust mostly prevalent in arid and semi-arid climates [24], hydrogen sulphide generated by algae on the ocean surface. O_3 which is the primary cause of greenhouse effect is produced naturally at ground level by the reaction between NOx and VOCs in the presence of daylight [25-26]. In some regions, vegetation also contributes to air pollution as it generates a substantial number of VOCs that reacts with the primary pollutants to emit various secondary pollutants [27]. Radioactive gases produced by radioactive decays such as radon and krypton if inhaled produces serious health hazards [28-29]. Forest fires can also add smoke particulates in the air atmosphere. The primary cause of air pollution is human activity [30]. The man-made sources can be further classified as stationary and mobile sources. Stationary sources include factories, power plants and industries whereas mobile sources include on-road vehicles, aircrafts and marine engines. Pollution caused by the running vehicles releases air-borne particles through exhaust emission produced from fuel combustion [31]. These PMs include various toxics such as benzene, formaldehyde (HCHO), 1, 3-butadiene and acetaldehyde. Coal-fired power stations generates both primary and secondary pollutants particularly $PM_{2.5}$. Industries produces pollutants such as NOx, SO_2, CO, VOCs and other PMs. Agricultural activities comprising fertilizers, livestock and soil management leads to release of ammonia, methane and nitrous oxide [32-33]. Further residential activities such as heating, cooking and use of household products generates various atmospheric particulates [34]. These toxic air pollutants have an impact on the environment, economy and human health worldwide. The poisonous chemicals present in the air react with the rain to produce acid rain that affects trees, crops, animals and can poison water bodies which eventually affects both human as well as aquatic life [35]. As it affects crops and agricultural fields, it lowers their yield and eventually leads to the dropping of economy scale. The most damaging impact of air pollution lies in its health impacts over human life as damage to anything can be tolerated but compromising with health is not acceptable. The most frequent causes of environmental air pollutants include coughing, sneezing, difficulty in breathing, asthma and lower respiratory infections. And if it continues to be consumed, it leads to rigorous health problems such as respiratory diseases, cardiovascular diseases, lung cancer and neurological disorders [36-39]. Accordingly, it is of utmost importance to generate advanced techniques for the treatment of these toxic pollutants. Figure 1 shows the schematic representation for the effects of air pollution on human health and various strategies for mitigating air pollution.

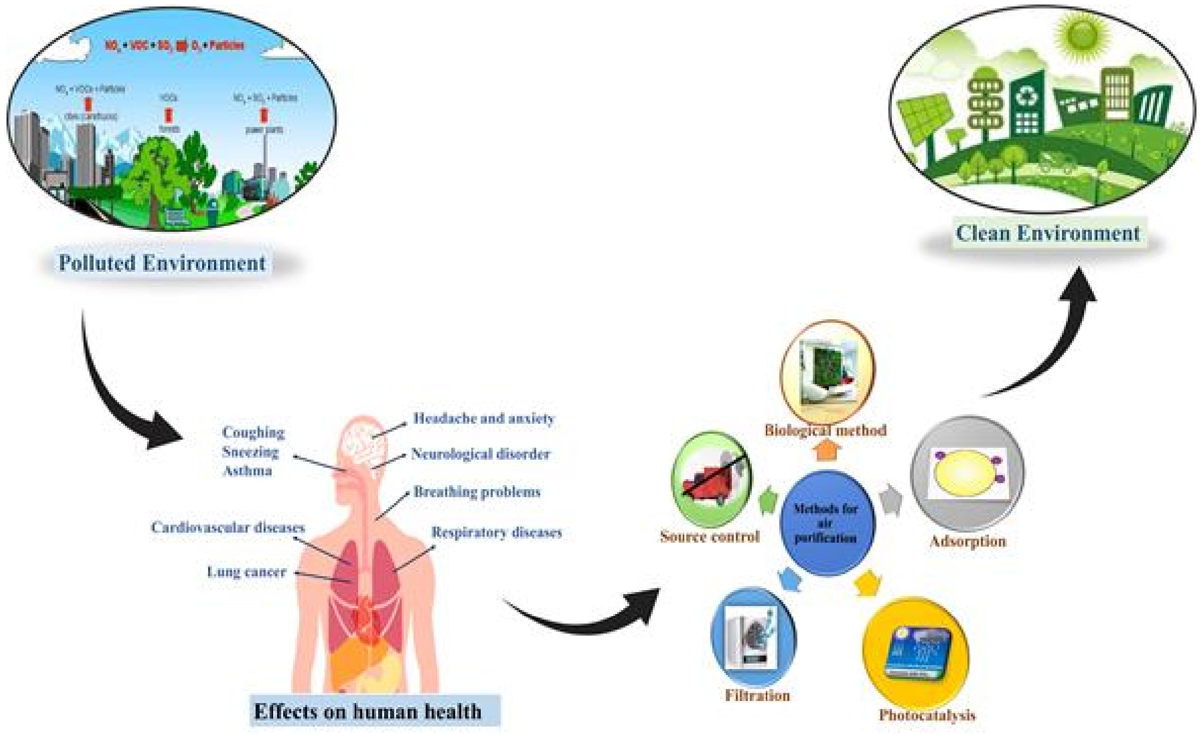

Fig. 1. Schematic representation depicting effects and methods for air pollutants removal.

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1.2. Methods to modulate air quality

Despite expansive knowledge about air pollution – its sources, causes and impacts on flora and fauna, considerable efforts are needed to prevent and mitigate it effectively. Addressing air pollution involves several key activities but the two most indeed approaches: SOURCE CONTROL and PURIFICATION by significant methods are helpful in drastically reducing air pollution.

1.2.1. Source Control

Source reduction is proactive strategy that focuses on tackling pollutants at their origin. It not merely prevents environmental damage but fosters more sustainable practices and frameworks, leading to productive use of resources and cost efficiency. The notable sources are– automobiles, pesticides, fossil fuels, livestock and many more household sources [40-42]. The main contributor of indoor pollution is consumption of traditional fuels such as cow dung and wood for cooking purposes, as these fuels provoke emission of PMs and VOCs in excessive amounts and pose health issues. According to Gautam et al. adopting cleaner fuels like LPG, coupled with improvements in ventilation and stove technology can lead to substantial benefits for air quality and public health [43].

Moreover, upgrading to more efficient electric cookstoves is another alternative that significantly lowers emissions and ultimately reduce pollutants. Likewise, transportation significantly impacts air quality with various effects stemming from vehicle emissions due to combustion of fossil fuels. Hakkim et al. [44] provided an updated emission inventory for road transport in India, covering various pollutants for the year 2015. This dataset includes 74 speciated VOCs, CO, NO_x, NH_3, CH_4, CO_2, $PM_{2.5}$, BC (black carbon), OC (organic carbon) and SO_2. It highlights that petrol-fuelled 2 and 3 wheelers, along with diesel-fuelled vehicles, are major sources of pollution in India and focuses on the potential impact of fleet substitution strategies that involves scenarios with gridded ($0.1° \times 0.1°$) emission projections resulting in reduced emissions, which directly improves air quality and reduces health risks associated with exposure to toxic substances and pollutants. Furthermore, Boonupara et al. [45] reviewed that pesticides get into air through pathways such that volatilization, spray drift, and soil emissions leading to contaminated air. He compiled effective and sustainable pest management strategies to mitigate environmental and health risks. Integrated Pest Management provides a holistic approach by incorporating various non-chemical methods, such as biological control, cultural practices, and the use of pest-resistant plant varieties and minimizes reliance on chemical pesticides, thereby reducing the potential for airborne pesticide exposure [46]. Thus, reduction of sources not only enhances air quality but also offers broad benefits for human health, ecosystems and the climate.

1.2.2. Purification methods There are various techniques for air treatment that can be used to control a variety of contaminants, including chemical (VOCs), physical (PMs), NO_2, ammonia and so on. The innovations have been broken down into two main groups: biological and physicochemical methods.

Biological Methods: These methods leverage natural processes and organisms to remove or neutralize pollutants from the air. Recent research has intensified on air purification mechanisms through phytoremediation, which utilizes plants to absorb and degrade airborne pollutants [47]. Technological advancements have improved the efficiency of plant-based systems, such as green walls, potted plants and biofilters, in enhancing indoor air quality and reducing contaminants like VOCs and CO_2 as reviewed by Prigioniero et al. [48], Jung and Awad [49], Dela Cruz et al. [50] and Irga et al. [51] in their studies. Furthermore, Microalgae-based air purification systems use microalgae's high photosynthetic efficiency to capture CO_2, produce O_2, and remove pollutants such as $PM_{2.5}$ and VOCs. Innovations include high-density microalgae films and closed photobioreactors integrated into building designs for enhanced indoor air quality [52]. Recent studies showcase the potential of microalgae for indoor air purification. For instance, Barati et al. [53] found that tobacco smoke affects the growth and lipid content of *Chlamydomonas* strains, with strain-specific responses indicating the need for careful species selection. Liu et al. [54] advanced air purification using soy protein isolate (SPI) from biomaterial, capitalizing on its 90% protein content and electrostatic properties to attract PMs (Figure 2). SPI integrates with bacterial cellulose (BC) from *Gluconacetobacter xylinus*, forming a 3D nanonetwork that physically filters PMs. By denaturing SPI with acrylic acid, particle size is reduced and enhanced interaction with airborne PMs. This innovative SPI-BC composite achieves outstanding filtration, removing 99.4% of $PM_{2.5}$ and 99.95% of PM_{10}.

Physicochemical Methods: Within the physicochemical technologies, filtration (mechanical and electronic) [55-56], adsorption [57], UV photocatalytic oxidation and ionization are included. The most common air cleaning technology for PMs (mechanical filters) use porous media to capture particles via impaction, interception, and diffusion. These filters are categorized by efficiency using standards like ISO 16890 and EN 1822, which include HEPA and ULPA filters for high air quality environments [58-61]. For instance, Liu et al. [62] designed a transparent polyacrylonitrile filter with 90% transparency, removing over 95% of $PM_{2.5}$, making it suitable for passive ventilation windows in urban areas. Also, electric filtration includes electrostatic precipitators and ionizers, which use electrical charges to remove particles from the air. Electrostatic precipitators can achieve over 90% efficiency for particles ranging from 0.3 to 6 µm claimed by Bliss [63]. Other than filtration, adsorption is also a prominent technique developed to enhance the retention of both VOCs and inorganic pollutants over

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adsorbents such as activated carbon (ACs), zeolites, silica gel, activated alumina, mineral clay, metal oxides and some polymers [64]. As in the case, Cheng et al. [65] assessed the antibacterial and regenerable properties of zeolite impregnated with metallic silver (Ag-Z) for effectively removing bioaerosols, such as bacteria and fungi from environments. UV-Photocatalytic oxidation is an advanced air cleaning technology that utilizes light-induced redox reactions to degrade gases and biological particles adsorbed on photocatalyst surfaces [66]. Titanium dioxide (TiO_2) is the most commonly used photocatalyst, as demonstrated by Weon et al. [67] in his study that TiO_2 nanotube photocatalyst can be utilized as filter for VOCs removal, used in a commercial indoor air cleaner. It achieved a 72% average VOCs removal efficiency within 30 minutes in an $8m^3$ test chamber. In addition, Bipolar ionization [68], created by applying AC voltage to electrodes, generates positive and negative ions that potentially purify air by producing $^{\cdot}OH$ radicals, which can deactivate microorganisms. Although the exact biocidal mechanisms are not fully established, these systems show promise in reducing bacteria, viruses, and VOCs, especially in long-term use [69]. Thus, these emerging technologies can enhance air quality, despite their limitations but employing carbon dots (CDs) synthesized from airborne particulates itself for pollution control is an innovative strategy. Hence, in this review we focus on methods that not only capitalizes on captured particulates but also integrates seamlessly with existing purification technologies, offering novel solution for improving air quality.

2. MEANS TO TRANSFORM ATMOSPHERIC PARTICULATE MATERIALS (PMS) TO CBNS

Carbon based nanomaterials (CBNs) are the materials that predominantly consists of carbon atoms. The flexible nature of the carbon atoms allows these materials to exhibit wide range of properties with numerous applications. Depending upon the lattice structure and arrangement of atoms, these CBNs are categorized into CDs, fullerenes, nanodiamonds, carbon nanotubes and graphene nanosheets [70-71]. CDs are a new class of nanomaterials with size range below 10 nm exhibiting unique chemical, optical and electronic properties which make it distinct from other carbon materials. These are quasi-spherical nanoparticles (NPs) containing various surface-active functional groups facilitating their solubility and reactivity. Fullerenes are a class of materials where carbon atoms are organized in the form of a hollow sphere or ellipsoid whereas nanodiamonds have diamond like crystal structure with their size in nm range. Carbon nanotubes exhibit one dimensional structure where carbon atoms are arranged in hexagonal lattice which further classified as single-walled and multi-walled carbon nanotubes. Graphene nanosheets are two-dimensional carbon nanomaterials with a thin layer in which sp^2 hybridized carbon atoms are filled compactly in a honeycomb-like structure.

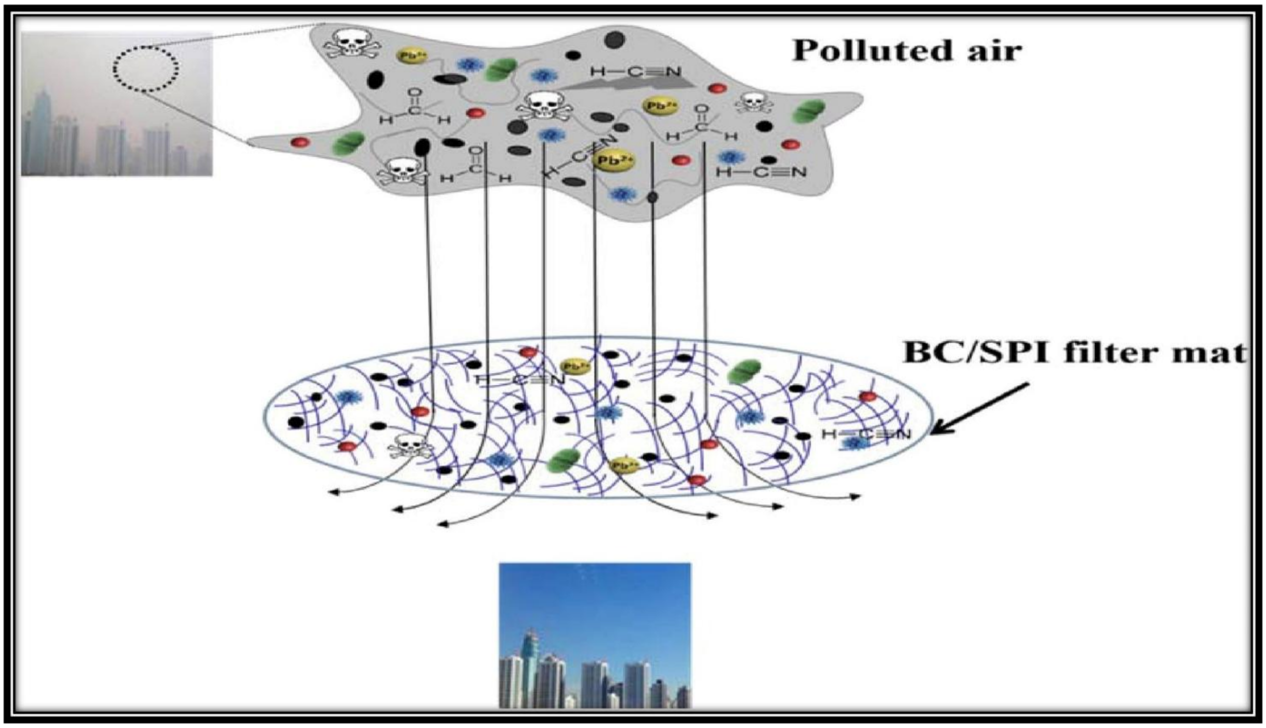

Fig. 2. Schematic representation of bio-based multi-functional air filtering material capturing various types of pollutants, Reprinted with permission from ref. [54], Liu, X., Souzandeh, H., Zheng, Y., Xie, Y., Zhong, W.H., and Wang, C., **2017**. Soy protein isolate/bacterial cellulose composite membranes for high efficiency particulate air filtration. *Composites Science and Technology*, *138*, pp. 124-133. Copyright @ Elsevier.

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2.1. Synthetic Methodologies:

As PMs poses a serious threat to human health, its mitigation is of utmost importance. Various studies have been reported till now for the purification of air pollution using zeolites, biosorbents, metal organic frameworks (MOFs), electrostatic precipitators, metal oxides and carbon-based materials [72-76]. Out of the diverse strategies used for the material synthesis for air purification, the transformation of the PMs itself into the CBNs precursors for air pollution mitigation are extensive in reach. Compared to other materials, the diversity in the synthesis techniques available for CBNs preparation make it a versatile option. There are two primary approaches for the synthesis i.e. top-down method and bottom-up method [77]. Figure 3 shows the concept of both approaches for CBNs synthesis from PMs using various methods. The bottom-up methods offer several advantages over top-down methods being environment friendly and less time requirement [78]. Table 1 shows the overview of all the methods used for CBNs synthesis from various carbon-based precursors.

Top-down methods: The top-down methods include the reduction or fragmentation of large carbon materials into CDs using chemical oxidation, laser ablation, chemical vapour deposition (CVD) and arc-discharge methods [79]. The most common top-down method used for the formation of CBNs from PMs are chemical oxidation methods. In particular, Srinivasan et al. [80] used kerosene fuel soot to synthesize fluorescent CDs using one pot oxidative acid treatment (HNO_3). The prepared CDs are 5 nm in size with outstanding stability against pH, light and salt effect. Gaddam et al. prepared CDs from camphor soot in the size range of ~ 1-4 nm [81]. Soot was treated with piranha solution [H_2SO_4:H_2O_2 (7:3)] followed by neutralization with sodium hydroxide and its dialysis for three days. Tripathi et al. [82] and Gunture et al. [83] designed water-soluble CDs and nanocarbons respectively from diesel soot using Soxhlet-purification technique followed by oxidative acid treatment.

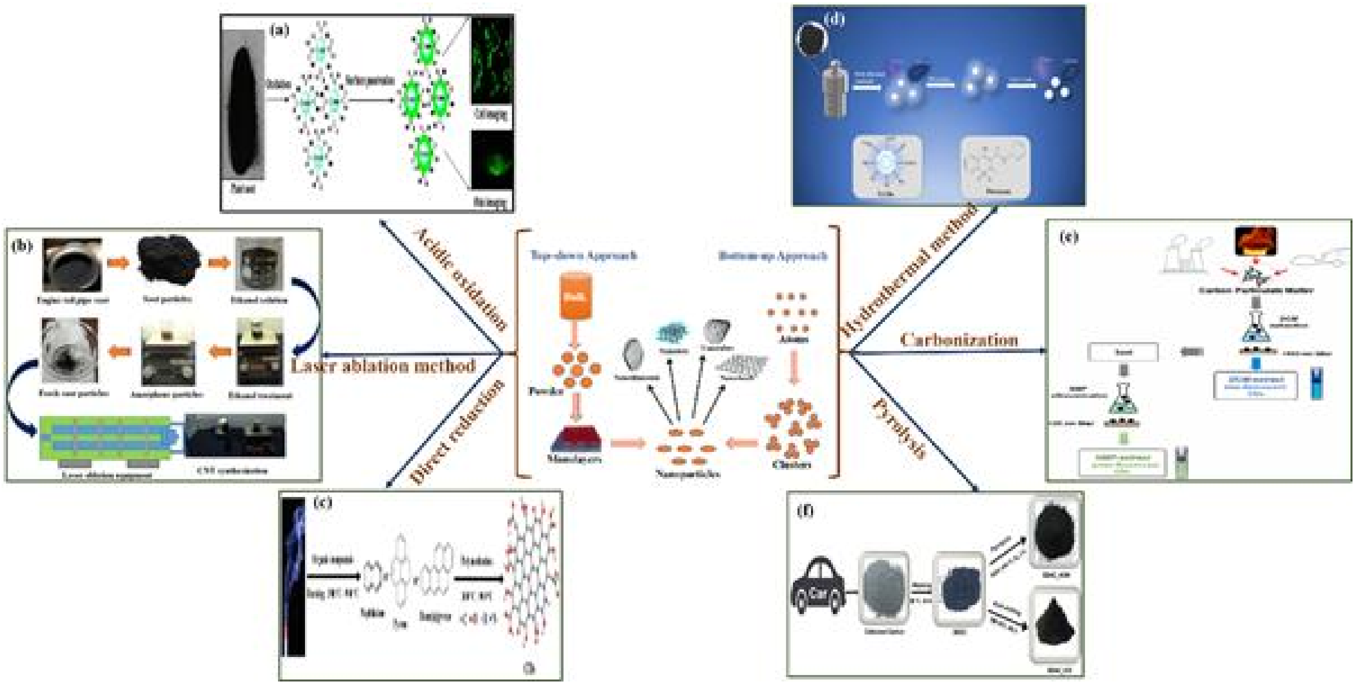

Fig. 3. Schematic illustration for top-down (a) acidic oxidation, Reprinted with permission from ref. [86], Tan, M., Zhang, L., Tang, R., Song, X., Li, Y., Wu, H., Wang, Y., Lv, G., Liu, W., and Ma, X., **2013**. Enhanced photoluminescence and characterization of multicolor carbon dots using plant soot as a carbon source. *Talanta*, 115, pp. 950-956. Copyright © Elsevier. (b) laser-ablation, (c) direct reduction, and bottom-up approaches (d) hydrothermal, Reprinted with permission from ref. [96], Zhang, J., Li, Q., Liu, Z., and Zhao, L., **2023**. Rapid and sensitive determination of Piroxicam by N-doped carbon dots prepared by plant soot. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 299, p. 122833. Copyright © Elsevier. (e) Carbonization, Reprinted with permission from ref. [98], Russo, C., Ciajolo, A., Stanzione, F., Tregrossi, A., and Apicella, B., **2023**. Separation and online optical characterization of fluorescent components of pyrogenic carbons for carbon dots identification. *Carbon*, 209, p. 118009. Copyright © Elsevier, and (f) pyrolysis, Reprinted with permission from ref. [94], Parida, S., Sahu, K.C., Sahoo, B.B., Pandey, V.S., Thatoi, D.N., Nayak, N., and Nayak, M.K., **2023**. High performance supercapacitor electrodes from automobile soots: An effective approach to control environmental pollution. *Inorganic Chemistry Communications*, p. 111671. Copyright © Elsevier.

Similarly, Sahu et al. [84] also derived carbon and its nanocomposites from diesel particulate to produce high performance energy storage material. Carbonaceous aerosols were used by Rabha et al. [85] for the synthesis of carbon nanodots using H_2O_2 as an oxidizing agent followed by ultrasonic treatment at a frequency of 40 KHz. Tan et al. [86] and Ganesan et al. [87] employed plant soot and candle soot for CDs preparation using chemical nitric acid oxidation method. Thulsi et al. reported water-soluble fluorescent CDs from vehicle exhaust waste soot using simple acid refluxion method (HNO_3) with particle size ~4 nm [88]. Direct reduction was also carried out to extract CDs as done by Li et al. where they extract CDs from cigarette smoke using $NaBH_4$ as reducing agent with particle size < 10 nm [89]. Gel separation technique can also be used for CDs extraction as done by Gunture et al. [90] where pollutant diesel soot (DS) was used as the precursor. The extraction process utilizes Soxhlet-purification technique using acetone to extract the acetone-soluble fluorescent fraction from the bulk DS. Then the solution was filtered using gel column to separate most fluorescent fraction of the solution. Apart from CDs, other CBNs were also fabricated via these atmospheric pollutants. To exemplify, Kowthaman and Arul Mozhi Selvan [91] synthesized carbon nanotubes from engine soot particles using laser ablation vaporization technique. The formed nanotubes result in an average size of 33 nm with high crystallinity and purity. Soluble graphene nanosheets were isolated from black carbon derived from petrol soot by Singh et al. [92] through sequential process, starting with Soxhlet purification and then an oxidative treatment to convert nanosheets into water soluble nanosheets. Nanodiamonds (NDs) like material were assembled by Islam et al. [93] from carbonaceous aerosols using ultrasonic-assisted oxidative chemical technique. A stable blue-fluorescence was observed with NDs with size of the particles to be 4-17 nm. It can be observed that the chemical oxidation method is the most favoured method for the synthesis of CBNs due to its versatility, effectiveness and ease of implementation.

Bottom-up methods: Bottom-up methods in nanotechnology and material science involves crafting structures from the smallest atomic or molecular units to the final desired scale. The widely used bottom-up techniques includes hydrothermal or solvothermal synthesis, microwave irradiation synthesis, electrochemical carbonization and extracting ACs from automobile soot [94]. Diesel engine exhaust carbon was converted into ACs using two distinct approaches (i) an acid treatment process and (ii) pyrolysis. Several CDs have been produced from air pollutants using hydrothermal technique. To consider, Aggarwal et al. [95], Zhang et al. [96], and Devi et al. [97] isolated nanocarbons and CDs from pollutant diesel soot, plant soot and vehicle generated pollutant soot respectively. All the above CBNs were derived using hydrothermal treatment. Russo et al. prepared blue fluorescent CDs from carbon particulate matter using carbonization method followed by ultra-sonification resulting in green fluorescent CDs [98].

2.2. Properties of CBNs

Carbon Based nanomaterials (CBNs) were characterized by their intricate microstructures, varying degrees of crystallinity and a broad range of sizes which collectively influence their diverse properties. Some key properties are optical properties (fluorescence, photostability, UV-Visible absorption [99-102]) and chemical properties (photocatalytic activity [103-104], chemical stability including biocompatibility [105] and dispersibility [106]) (Figure 4). Due to these properties, CBNs are at the cutting edge of innovation-they light up biological pathways with their tunable fluorescence, navigate drugs directly to their targets with pinpoint precision and detect environment pollutants with sharp sensitivity. Thus, spectrum of these multifaceted properties is explored below:

2.2.1. Optical Properties

Carbon nanomaterials, including graphene, carbon nanotubes and fullerenes, exhibit a range of remarkable optical properties that are largely attributable to their distinct structural characteristics and electronic configurations. Graphene, with its two-dimensional honeycomb lattice of carbon atoms, demonstrates strong absorption across a wide range of the electromagnetic spectrum, from UV to infrared, due to its π-electron cloud's strong interaction with photons. This broad-spectrum absorption can be leveraged in cutting-edge technologies like high-efficiency photodetectors, adaptive optical modulators and tunable filters [107-110]. Semiconducting carbon nanotubes exhibit strong and size-dependent photoluminescence in the near-infrared region, which is valuable for bioimaging and diagnostic applications. Their unique raman scattering signatures provide insights into their electronic structure and can be used for sensing applications [111-113]. Fullerenes, with their spherical cage-like structure, showcase unique optical features, including strong absorption bands and electronic transitions related to their π-electron system [114-115]. In additional to all above, carbon nanodots are a captivating type of nanomaterial celebrated for their exceptional optical characteristics and broad range of applications. They exhibit strong fluorescence, photostability and UV-visible absorption [116] as given below:

Fluorescence: Carbon nanodots are distinguished by their ability to emit fluorescence across a broad spectrum, ranging from blue to red wavelength. This broad emission range is closely tied to the size of the CDs: smaller CDs generally emit light of shorter wavelength while larger ones emit longer wavelengths. Additionally, the emission properties of CDs can be tailored through surface

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functionalization that results in modification of their optical behavior [117-119]. This ability to tune fluorescence emission make CDs highly versatile for applications, such as multi-color imaging and multiplexed assays [120-121]. The outstanding quantum yields, which underscore their ability to efficiently convert absorbed photons into emitted fluorescence. This elevated quantum yield means that a large fraction of the light absorbed by the CDs is re-emitted as vibrant, intense fluorescence resulting in bright, clear, sensitive and highly precised optical applications [122]. Thulasi et al. [88] explores converting vehicle exhaust soot into fluorescent carbon dots via a simple acid refluxion method. These spherical CDs with an average size of 4 nm, exhibit unique excitation-dependent fluorescence properties, enabling them to detect tartrazine, a common food dye, with remarkable limit of detection (LOD) of 26 nM. Zhang et al. [96] introduces a novel approach detecting piroxicam (PX) using fluorescent nitrogen-doped carbon dots (N-CDs) synthesized via hydrothermal method from plant soot and ethylenediamine. The study achieved an impressive detection range of 6–700 μg/mL and ultra-low LOD at 2 μg/mL. Furthermore, Tripathi et al. [82] develops a method for synthesizing water-soluble fluorescent CDs from diesel soot, an environmental pollutant. These exhibit multicolored fluorescence and are used to label *Escherichia coli (E. coli)* and fluorescence can be quenched by methylene blue (MB), which is reversed by cholesterol, demonstrating a dynamic "turn-off" and "turn-on" response which highlights the potential of soot-derived CDs for advanced biosensing.

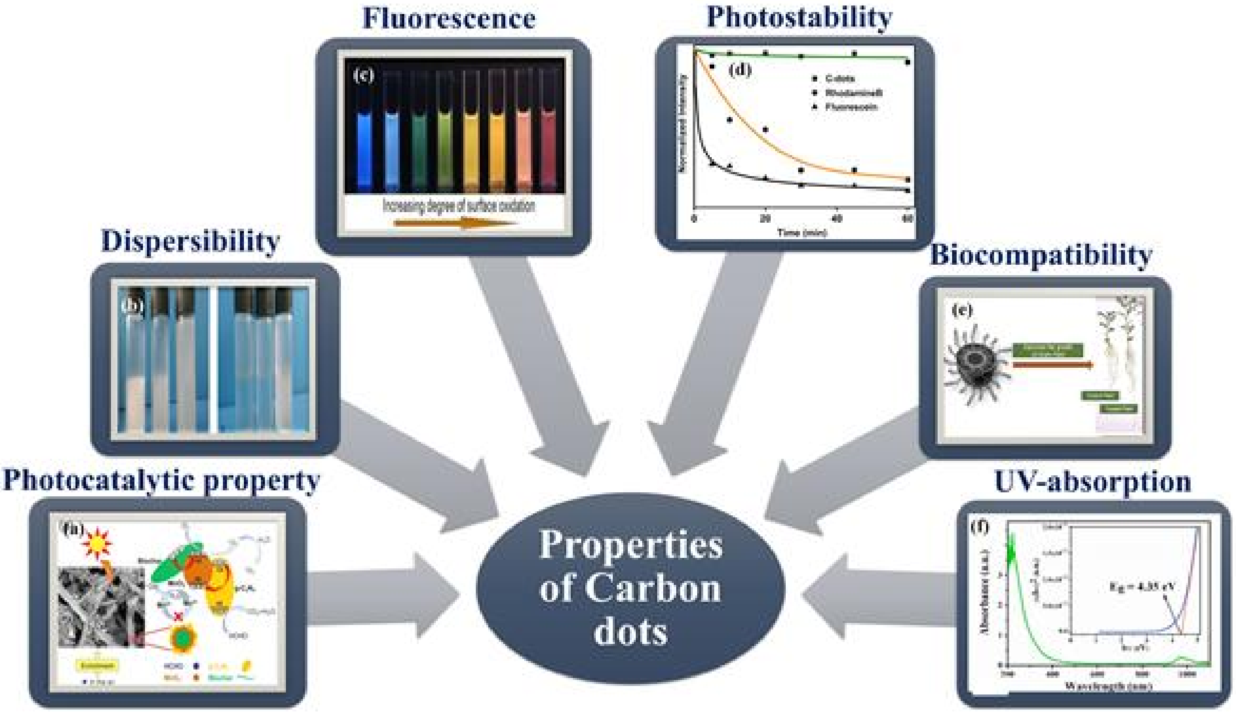

Fig. 4. Schematic illustration for diverse chemical and optical properties of CBNs (a) photocatalytic property, Reprinted with permission from ref. [135], Li, X., Fang, G., Qian, X., and Tian, Q., **2022**. Z-scheme heterojunction of low conduction band potential MnO_2 and biochar-based $g-C_3N_4$ for efficient formaldehyde degradation. *Chemical Engineering Journal*, 428, p. 131052. Copyright © Elsevier. (b) dispersibility, (c) fluorescence, Reprinted with permission from ref. [144], Ding, H., Yu, S.B., Wei, J.S., and Xiong, H.M., **2016**. Full-color light-emitting carbon dots with a surface-state-controlled luminescence mechanism. *ACS Nano*, 10(1), pp. 484-491. Copyright © American Chemical Society. (d) Photostability, Reprinted with permission from ref. [86], Tan, M., Zhang, L., Tang, R., Song, X., Li, Y., Wu, H., Wang, Y., Lv, G., Liu, W., and Ma, X., **2013**. Enhanced photoluminescence and characterization of multicolor carbon dots using plant soot as a carbon source. *Talanta*, 115, pp. 950-956. Copyright © Elsevier. (e) Biocompatibility, Reprinted with permission from ref. [139], Aggarwal, R., Garg, A.K., Kaushik, J., and Sonkar, S.K., **2020**. Pollutant-based onion-like nanocarbons for improving the growth of gram plants. *Materials Today Chemistry*, 18, p. 100352. Copyright © Elsevier. and (f) UV-absorption, Reprinted with permission from ref. [128], Chaudhary, P., Verma, A., Mishra, A., Yadav, D., Pal, K., Yadav, B.C., Kumar, E.R., Thapa, K.B., Mishra, S., and Dwivedi, D.K., 2022. Preparation of carbon quantum dots using bike pollutant soot: Evaluation of structural, optical and moisture sensing properties. *Physica E: Low-dimensional Systems and Nanostructures*, 139, p. 115174. Copyright © Elsevier.

Table 1. Outlook of the reported precursors and methodologies for synthesizing various CBNs from PMs.

Precursors	Synthetic methodology	Solvent /Reagent	Type of CBNs	Ref.
TOP-DOWN APPROACH				
Kerosene fuel	Oxidative acid treatment	HNO_3	CDs	[80]
Camphor soot	Oxidative acid treatment	Piranha solution[H_2SO_4: H_2O_2 (7:3)]	CDs	[81]
	Oxidative acid treatment	HNO_3	CDs	[82]
Diesel soot	Oxidative acid treatment	HNO_3	Onion-like Nanocarbons	[83]
	Gel separation technique	Acetone	CDs	[90]
Diesel particulates	Acidic oxidation	H_2SO_4	Carbon nanocomposites	[84]
Carbonaceous aerosols	Oxidation followed by ultra-sonification	H_2O_2	Carbon nanodots	[85]
	Ultrasonic assisted oxidative chemical technique	H_2O_2	Nanodiamonds	[93]
Plant soot	Ultrasonic treatment	HNO_3	CDs	[86]
Candle soot	Acidic oxidation	HNO_3	CDs	[87]
Vehicle exhaust waste soot	Acid refluxion method	HNO_3	CDs	[88]
Cigarette smoke	Direct reduction	$NaBH_4$	CDs	[89]
Engine soot	Laser ablation technique	Methyl ester	Carbon nanotubes	[91]
Petrol soot	Oxidative treatment	HNO_3	Graphene nanosheets	[92]
BOTTOM-UP APPROACH				
Automobiles soot	Acidic treatment followed by pyrolysis	HCl	Activated carbon	[94]
Diesel pollutant	Hydrothermal treatment	NH_4OH	Nanocarbons	[95]
Plant soot	Hydrothermal treatment	Ethylenediamine	CDs	[96]
Vehicle generated soot	Hydrothermal treatment	Distilled waterHNO_3	CDs1CDs2	[97]
Carbon particulate matter	Carbonization	_	CDs	[98]

Photostability: Photostability in CDs signifies their ability to sustain fluorescence even after prolonged light exposure. High photostability is crucial for applications in imaging, sensing, and biological labelling, where prolonged illumination is often necessary [123]. Their exceptional photostability stems from their robust carbon-based core, which adeptly neutralizes reactive oxygen species and other by-products that usually cause photobleaching [124]. Tan et al. [86] investigated that CDs formed from plant soot by oxidative treatment demonstrates outstanding photostability compared to organic dyes like fluorescein and rhodamine B (RhB). Even after exposure to 40 W incandescent lamp for 60 minutes, the fluorescence intensity of the CDs remains stable, whereas fluorescein and RhB show reductions of 89% and 82% respectively. This superior stability leads high suitability of CDs as fluorescent probes for live cell imaging, advanced microscopy and various analytical applications. Moreover, Gunture et al. [90] pioneered streamlined isolation method for extraction of fluorescent CDs from pollutant DS by employing a Soxhlet extraction with acetone. These CDs exhibit robust photostability for upto 4 hrs with 8% quantum yield.

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UV-visible Absorption: To better understand CDs luminescence, researchers focus on UV-visible absorbance that reflects difference in chemical structures. UV-visible absorption properties of CDs provide insights into their electronic structure and functionalization. In the UV region (200-400 nm), they typically show broad absorption due to π-π* transitions of C=C bonds and n-π* transitions of surface functional groups [125-127]. Chaudhary et al. [128] research work reveals that bike pollutant soot can also be transformed into CQDs via hydrothermal method. These quantum dots exhibited green fluorescence under UV light and thus, not only mitigates pollution by repurposing soot but also yields valuable nanomaterials. Similarly, Egorova et al. [129] focused on the optical and structural properties of CDs synthesized through hydrothermal processing using citric acid, glucose and birch bark soot as precursors. It revealed that various oxygen and nitrogen functional groups, such as hydroxyl, carboxyl, carbonyl, amino and nitro groups result in strong UV absorption in the 200–300 nm range leading to multifaceted uses.

2.2.2. Chemical Properties:

CDs exhibits a range of chemical properties that make them highly versatile. Their surface is often functionalized with groups like hydroxyl, carboxyl, carbonyl, amino and nitro which influence their solubility, reactivity and interaction with other substances and also size and shape of CDs can affect their chemical behaviour [130-131]. Thus, chemical properties mainly include photocatalytic activity, dispersibility and biocompatibility offering varied applications as discussed below:

Photocatalytic activity: CDs can harness light to drive reactions and can generate reactive species that break down organic pollutants and contaminants. This property makes them effective for applications like purifying water, cleaning air and addressing environmental pollution [132-134]. Li et al. [135] developed a novel MnO_2 photocatalyst exhibiting an unusually low conduction band potential of -1.09 V, a significant improvement over previously reported MnO_2 materials. It was also followed by advancement as a biochar/MnO_2/g-C_3N_4 photocatalyst which demonstrated a remarkable HCHO degradation efficiency of 91.78%. In addition to this, Zhang et al. [136] reveals effective route for tailoring porous carbons for efficient VOCs removal by pre-treating crude biomass with microbial lignocellulose decomposition. This method produced high specific surface areas (up to 2290 m^2/g) and unique needle-like porous structures leading to enhanced properties.

Bio-compatibility: CDs are increasingly recognized for their biocompatibility and minimal cytotoxicity allowing them to be used safely for cellular imaging and drug delivery. Their biocompatibility is further enhanced by their size, surface charge, and functionalization [137-138]. Recent advancements in utilizing waste materials have led to the development of amine-functionalized onion-like nanocarbons (ONC-NH_2) from black diesel soot studied by Gunture et al. [139] and these ONC-NH_2 serve as efficient, biocompatible fluorescent probes for cancer cell imaging. Egorova et al. [129] explored and concluded that CDs formed from bark of tree is ecological and no toxic resulting into varied biomedical applications (Figure 5).

Dispersibility: The dispersibility of CDs is influenced by surface functionalization which can enhance solubility in specific solvents-hydrophilic groups improve aqueous solubility while hydrophobic groups are better for organic solvents. Additionally, stability in solution is affected by factors such as pH and ionic strength that is vital to prevent aggregation [140-142]. Optimization of these factors ensures that CDs remain well-dispersed and effective for their intended biological uses. Zhao et al. [143] studied the water-soluble CDs formed from smoke of cigarette which led to neuroendocrinological and neurotransmitter changes in mice due to water dispersibility.

3. ROLE OF CBNs IN AIR PURIFICATION

In recent years, several innovative strategies have been employed for air purification. Martínez-Montelongo et al. [146] fabricated visible light active TiO_2-Cu^{2+}@perlite and Ag@TiO_2-Cu^{2+}/perlite supported materials to build a photocatalytic air purifier for air purification. Metal based materials were also prepared to alleviate air pollutants. For example, Le et al. developed alumina beads decorated copper-based coordination polymer for the removal of VOCs and *E. coli* pathogen pollutants [147]. Mavrikos et al. formed Zn/Cu metal ion modified natural palygorskite clay–TiO_2 nanocomposites for outdoor and indoor air de-pollution [148]. However, the most widely used materials for air pollution mitigation involves the use of CBNs. CBNs have been deployed mostly through two innovative strategies: adsorption and photocatalysis.

3.1. CBNs and their hybrids as effective adsorbent for harmful gases

Adsorption method is a technique used to remove contaminants from gases or liquids by adhering them to the surface of an adsorbent material [149]. It can be physical or chemical depending upon the interactions between the adsorbent and the surface being removed. This approach is not only energy-efficient but also allows for the reuse and regeneration of the adsorbents. CBMs supports the formulation of high-performance adsorbent materials. For instance, nitrogen doped porous carbons were prepared by Yu et al. for the adsorptive removal of hydrogen sulphide gas (H_2S) [150]. Gou and Yarahmadi prepared luminescent graphene quantum dots (GQDs) and MWCNTs as a

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photocatalytic sorbent for the removal of toxic ethylbenzene from air in presence of UV radiation [151]. Graphene oxide/ordered mesoporous carbon (GO/OMC) nanostructures were derived by Szczęśniak et al. for the adsorption of various gases such as CH_4, CO_2, H_2 and C_6H_6 [152]. Carbon materials can also be processed to have a large surface area and making it remarkably effective for adsorption by using any activating agent like potassium hydroxide (KOH) or zinc chloride ($ZnCl_2$). Many researchers have prepared ACs for the removal of air pollutants as it manifests good adsorptive power. To consider, Ligotski et al. [153], Ogungbenro et al. [154], Wang et al. [155], Kazmierczak-Razna et al. [156], Goncalves et al. [157] and Zhang et al. [158] reported the use of activated carbon efficiently for the eradication of various VOCs and toxic gases like H_2S, toluene, CO_2, NO_2, CH_4 etc. Innovatively, turning adversaries into allies i.e. the pollutants itself are being harnessed to combat pollution converts the problem into a solution in the fight against air pollution. Li et al. prepared ACs from petroleum coke using KOH activation which was further used for the CO_2 adsorption [159].

For CF_4 adsorption which was considered to be prominent global warming compound that worsens climatic change, Yuan et al. derived chemically activated microporous carbons from petroleum coke [160]. The adsorption uptake was found to be higher i.e. 2.79 mol kg^{-1} at 25°C and 1 atm pressure. Li et al. [161] prepared porous carbons by KOH activation of rice husk char and utilized it for CO_2 capture at low pressure. Also, several hybrid systems have been ingeniously devised to address and minimize several issues. The necessity for hybrid systems arises from the limitations of individual air purification methods that involves less efficiency, low reliability and limited pollutant removal. Kiani et al. [162] prepared ASZM-TEDA carbon (carbon impregnated with copper, silver, zinc, molybdenum and triethylenediamine) and a comparative analysis was given of ASZM-TEDA carbon and raw activated carbon for the adsorption of SO_2 and NO_2 gases. Comparatively, ASZM-TEDA carbon demonstrated a superior adsorption ability increasing by up to 31.5% for NO_2 and 55.9% for SO_2. Owing to the strong chemical interactions between Pt and the coordinated atoms (C, N, O and S atoms) present in the air molecules due to overlapping of 5d orbitals of Pt and the outermost p orbitals of the coordinated atoms, Pt decorated carbon nanotubes were designed by Yang et al. [163] for the removal of most common air pollutants with good recovery performance. Zhong et al. developed a covalent organic framework hosting metalloporphyrin based CDs for CO_2 adsorption [164]. Here metalloporphyrin have been used as homogeneous catalysts for effective CO_2 adsorption exhibiting exceptional catalytic activity and selectivity. Also, graphene features a high specific surface area, adjustable chemical properties, good porosity and mechanical properties. Guo et al. [165] prepared graphene oxide/carbon composite nanofibers for the adsorption of benzene and butanone. CNT-enhanced amino functionalized and silica modified graphene aerogels were synthesized by Wu et al. [166] and Li et al. [167] for the effective removal of HCHO and other toxic pollutant gases respectively. Therefore, the composite nanomaterials demonstrated to possess strong adsorption power in comparison to pure materials. Other previous reported literature has been provided in Table 2.

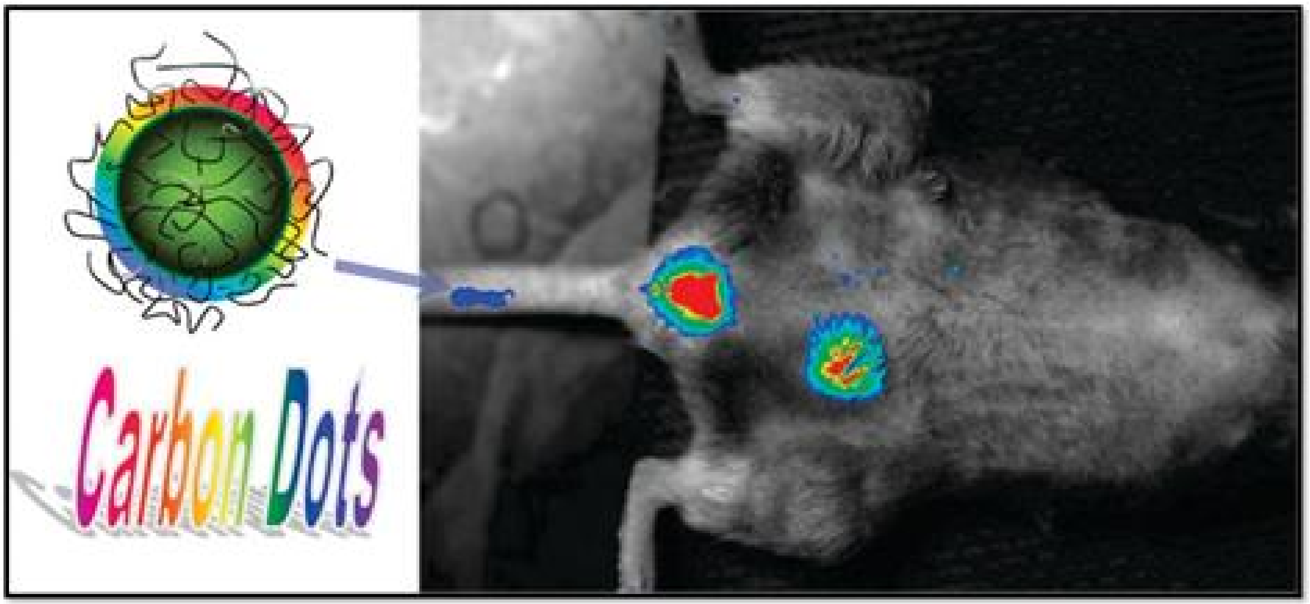

Fig. 5. Biocompatibility of CDs for bioimaging and biomedical applications, Reprinted with permission from ref. [145], Yang, S.T., Cao, L., Luo, P.G., Lu, F., Wang, X., Wang, H., Meziani, M.J., Liu, Y., Qi, G., and Sun, Y.P., **2009**. Carbon dots for optical imaging in vivo. *Journal of the American Chemical Society*, 131(32), pp. 11308-11309. Copyright © American Chemical Society.

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Mechanism of adsorption: CBNs are at the forefront as some of the most versatile adsorbents, playing a crucial role for air pollutants removal. Various mechanisms such as electrostatic interactions, π- π bonding and hydrophobic interactions can influence the adsorption behaviour. For instance, Wu et al. [166] investigated that the CNT-enhanced graphene aerogel offers superior HCHO removal through both physical and chemical mechanisms. Within its microstructure, CNTs reinforce and link the graphene sheets that reduce pore diameter and increase specific surface area. This optimized pore structure enhances the physical adsorption of HCHO. In addition, their research showed that CNTs results in improvement of HCHO capturing by chemical modifications due to reduced aggregation followed by more exposure to functional groups. Similarly, Shao et al. employed CO_2 activation with biochar to enhance the SO_2 adsorption [176]. The impregnation of biochar with CO_2 developed a pore structure that enhance vanderwaal forces for SO_2 capture. Schematic diagrams for adsorption mechanisms of SO_2 pollutant was shown in Figure 6.

3.2. Efficacy of CBNs and their hybrids in Photocatalytic conversion of toxins

The photodegradation process for air pollutants removal involves the use of light energy to decompose harmful substances present in the air. This process involves photocatalysts that upon exposure to light generate reactive species such as hydroxyl radicals which further breakdown pollutants into harmless or less harmful byproducts. Graphitic carbon nitrides (g-C_3N_4) is the most stable allotrope in the family of carbon nitrides and have thermal stability of upto 500°C [177]. g-C_3N_4 excel as photocatalyst due to their robust layered structure and strong visible light absorption. Their extreme stability, cost-effectiveness and superior charge carrier management makes them highly effective for environmental remediation applications. To consider, Zilli-Tomita et al. used g-C_3N_4 as a photocatalyst and to enhance its effectiveness, performance and porosity for the treatment of vapor iso-butanol, its composite with ACs was prepared [178]. Several researchers including Yue et al. [179], Yao et al. [180], Kong et al. [181] and Song et al. [182] developed porous g-C_3N_4 for the effective elimination of HCHO which is a common air pollutant known for its toxicity. Baudys et al. also prepared g-C_3N_4 for acetaldehyde and NO_x removal [183]. In conclusion, g-C_3N_4 are pivotal in air pollution mitigation strategies. Metal based g-C_3N_4 were also introduced to enhance their photocatalytic activity for pollutants removal. Wang et al. fabricated silver NPs decorated g-C_3N_4 photocatalyst film for the effective removal of HCHO and VOCs [184].

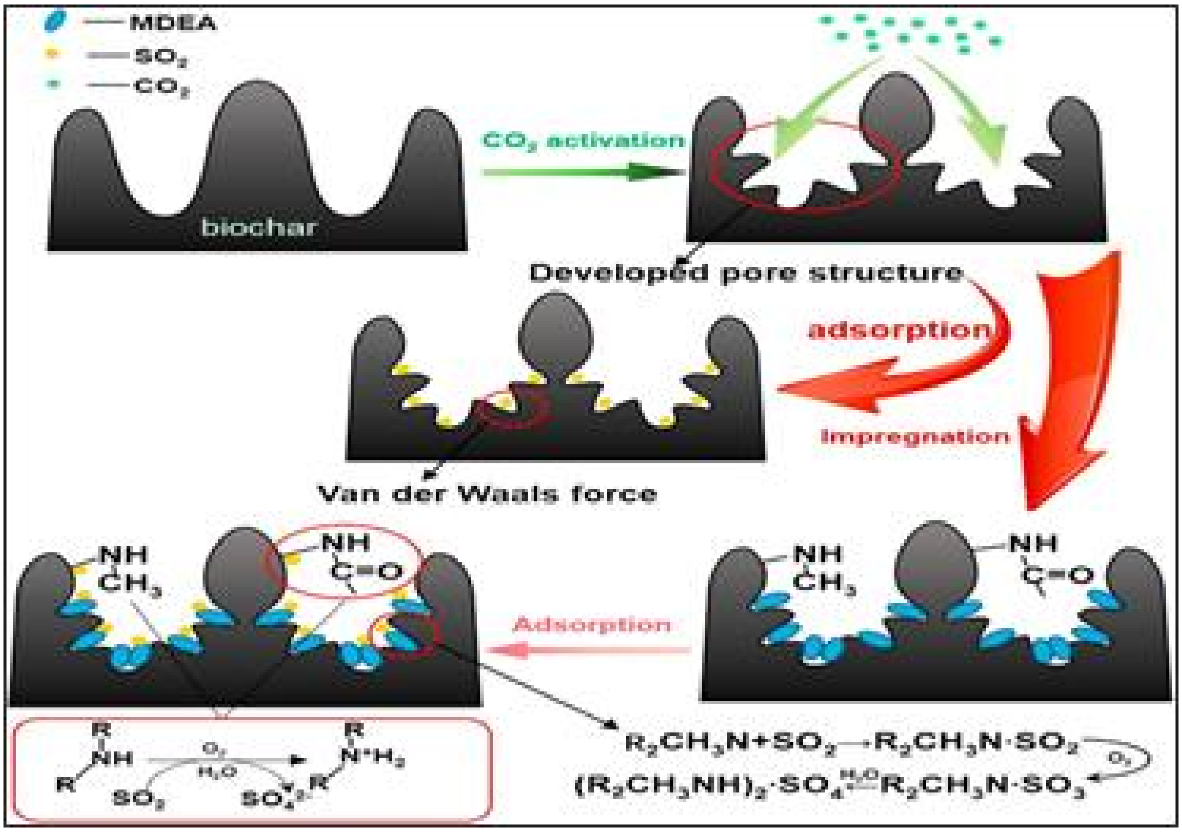

Fig. 6. Pictorial representation of adsorption mechanisms for SO_2 removal. Reprinted with permission from ref. [176] Shao, J., Zhang, J., Zhang, X., Feng, Y., Zhang, H., Zhang, S., and Chen, H., **2018**. Enhance SO_2 adsorption performance of biochar modified by CO_2 activation and amine impregnation. *Fuel*, 224, pp. 138-146. Copyright © Elsevier.

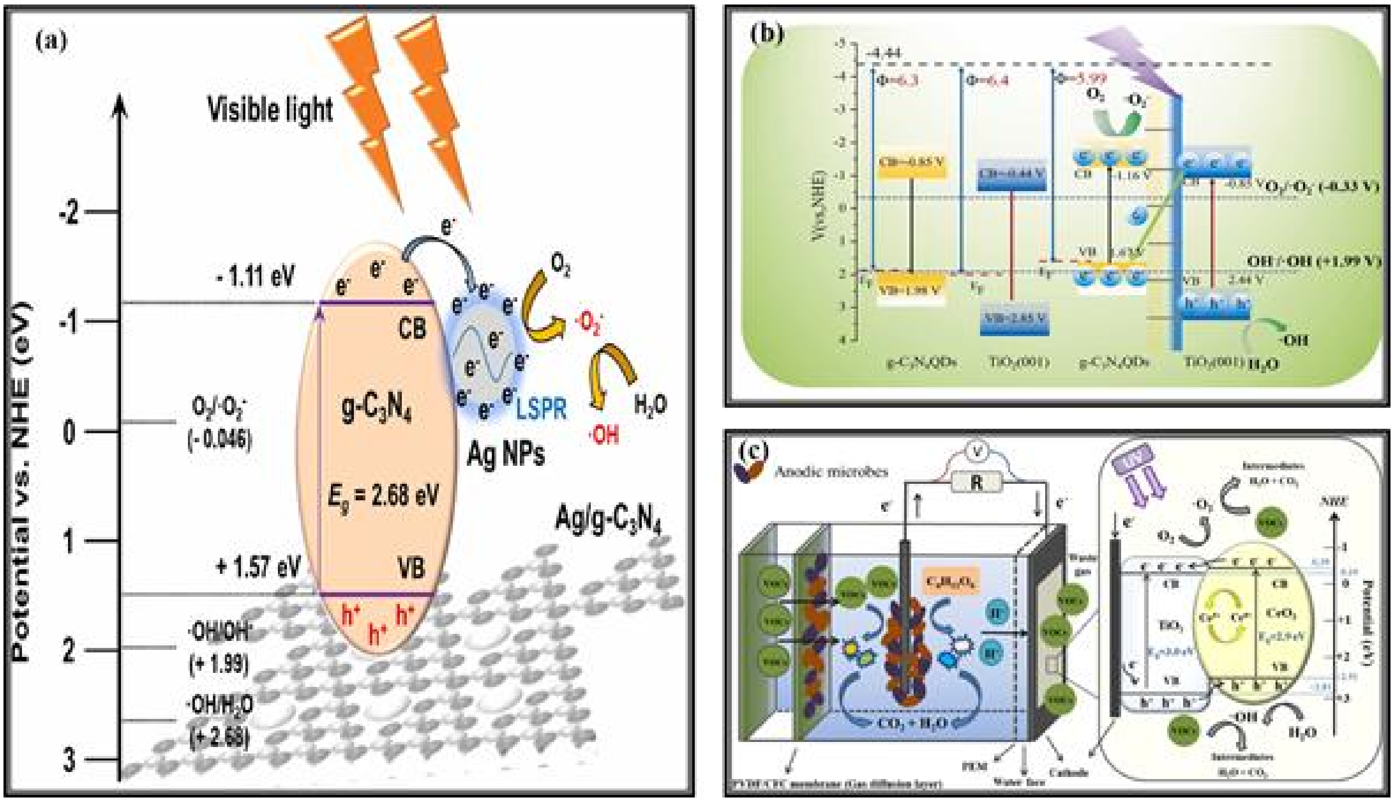

Fig. 7. Representation of photocatalytic mechanism for pollutants degradation (a) Ag/g-C_3N_4, Reprinted with permission from ref. [184], Wang, F., Li, W., Zhang, W., Ye, R., and Tan, X., **2022**. Facile fabrication of the Ag nanoparticles decorated graphitic carbon nitride photocatalyst film for indoor air purification under visible light. *Building and environment*, 222, p. 109402. Copyright © Elsevier. (b) g-C_3N_4QDs and TiO_2, Reprinted with permission from ref. [192], Li, Q., Zhang, S., Xia, W., Jiang, X., Huang, Z., Wu, X., Zhao, H., Yuan, C.S., Shen, H., and Jing, G., **2022**. Surface design of g-C_3N_4 quantum dot-decorated TiO_2 (001) to enhance the photodegradation of indoor formaldehyde by experimental and theoretical investigation. *Ecotoxicology and environmental safety*, 234, p. 113411. Copyright © Elsevier, and (c) UV-assisted PEC-MFC system, Reprinted with permission from ref. [193] Chen, Q., Liu, L., Liu, L., and Zhang, Y., **2020**. A novel UV-assisted PEC-MFC system with CeO_2/TiO_2/ACF catalytic cathode for gas phase VOCs treatment. *Chemosphere*, 255, p. 126930. Copyright © Elsevier.

Molybdenum doped and zirconium MOFs based g-C_3N_4 were utilized by Wang et al. [185] and Shi et al. [186] for the photocatalytic reduction of CO_2. Since TiO_2 is a widely renowned photocatalyst because of its broad-spectrum light absorption power and high efficiency to generate reactive oxygen species for its effectiveness in a range of environmental applications. For instance, Graphene oxide-TiO_2 photocatalyst developed by Tai et al. [187] for photocatalytic oxidation of methanol. Mahmood et al. [188] and Shu et al. [189] devised CQDs-TiO_2 nanocomposite and Mn/TiO_2/activated carbon composite respectively for the effective photodegradation of VOCs. There is also a substitute for TiO_2 i.e. Bi_2WO_6 which is also known as non-titanium catalyst that can be used for photocatalysis because of their non-toxicity and visible light responsivity. BiOI/Bi_2WO_6/ACF composite was prepared by Wang et al. for toluene removal [190] and CQDs decorated Bi_2WO_6 nanocomposites were developed by Qian et al. [191] for photocatalytic oxidation of gaseous acetone and toluene.

Mechanism of photocatalytic oxidation for removal of airborne pollutants: The scavenger experiments presented that photo-generated holes and superoxide radical anions were the primary active species leading to photocatalytic degradation of VOCs and deactivation of microorganisms (Figure 7). To consider, Wang et al. investigated the photocatalytic mechanism of the Ag/g-C_3N_4 film involving a series of intricate steps which were elucidated through scavenger experiments [184]

(i) Electron excitation and charge separation: The g-C_3N_4 photocatalyst absorbs visible light due to its band gap of 2.68 eV which excites electrons from the valence band (VB) to the conduction band (CB). The conduction band edge potential of g- C_3N_4 is more negative than the fermi level of the Ag NPs. Consequently, photo-generated electrons migrate from the CB of g-C_3N_4 to the surface of Ag NPs which facilitates charge separation.

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(ii) Formation of Superoxide Radicals: The electrons accumulated on Ag NPs react with molecular oxygen present on the catalyst surface. This interaction generates superoxide radical anions ($\cdot O_2^-$).

(iii) Generation of hydroxyl radicals ($^{\cdot}OH$): The superoxide radical anions react with water to produce $^{\cdot}OH$ and hydroxide ion. The involving reaction is:

$$\cdot O_2^- + 2H_2O \longrightarrow 2^{\cdot}OH + 2OH^-$$

(iv) Photocatalytic degradation: The superoxide radicals and photo-generated holes primarily drive the degradation of VOCs and the inactivation of microorganisms. While $^{\cdot}OH$ contribute to the photocatalytic process, their role is minor compared to superoxide radicals and holes. The Ag/g-C_3N_4 photocatalyst effectively utilizes visible light to drive these reactions, leading to the degradation of harmful compounds. Furthermore, Li et al. [192] investigates the photodegradation of HCHO using TiO_2 and 7:1 g-C_3N_4QDs/TiO_2 catalysts, demonstrating enhanced performance with the latter. The Z-scheme mechanism proposed shows that electrons from TiO_2 move to g-C_3N_4QDs, facilitating the generation of $^{\cdot}OH$ and $\cdot O_2^-$ radicals. Under UV irradiation, HCHO decomposes on TiO_2 via a photo-oxidation pathway observed through in-situ DRIFT spectroscopy.

Table 2. Various CBNs used for the removal of various tyles of targeted pollutants.

S. No.	Types of CBNs	Doping material used	Target pollutant	Ref.
Removal of pollutants via adsorption				
1.	**Porous carbons**	Nitrogen doped	H_2S	[150]
2.	**Graphene QDs and multi-walled carbon nanotubes**	-	Ethylbenzene	[151]
3.	**Mesoporous carbon**	Graphene oxide	H_2, C_6H_6, CH_4, CO_2	[152]
4.	**Activated carbon**	-	Toluene	[153]
		-	CO_2	[154]
		-	H_2S	[155]
		-	NO_2 and H_2S	[156]
		-	H_2S and mixtures with CH_4, and CO_2	[157]
		-	Toluene	[158]
		-	CO_2	[159]
5.	**Chemically activatedmicroporous carbons**	-	CF_4	[160]
6.	**Porous carbons**	KOH activation	CO_2	[161]
7.	**Activated carbon**	ASZM-TEDA	NO_2, SO_2	[162]
8.	**Carbon nanotubes**	PtN_3 doped	CO, NO, NO_2, SO_2, SO_3, NH_3, H_2S, O_3	[163]
9.	**CDs**	Metalloporphyrin	CO_2	[164]

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10.	**Carbon nanofibers**	Graphene oxide	C_6H_6 and butanone	[165]
11.	**Carbon nanotubes**	Amino functionalizedgraphene aerogel	HCHO	[166]
12.	**Graphene aerogels**	Tetraethyl orthosilicate	Benzene and Toluene	[167]
13.	**Activated carbon**	Silver nanoparticles	HCHO	[168]
14.	**Porous carbon spheres**	Silica modified	CO_2	[169]
15.	**Cellulose nanofibers**	N and S doped CDs	VOCs	[170]
16.	**Carbon nanofilaments**	Iron oxide	H_2S	[171]
17.	**Graphene quantum dots**	SnO_2 Doped	NO	[172]
18.	**Activated carbon**	ZnO-CuO	H_2S	[173]
19.	**Activated carbon fibers**	MnO_2	NO	[174]
20.	**Activated carbon**	α - FeOOH	H_2S	[175]
Removal of pollutants via photocatalytic oxidation				
1.	**g-C_3N_4**	-	Iso-butanol	[178]
2.	**Graphitic carbon nitride**	-	HCHO	[179]
		-	HCHO	[180]
		-	Acetaldehyde and NO_X	[183]
3.	**Carbon nitride nanosheets**	-	HCHO	[181]
4.	**Graphitic carbon nitride nanosheets**	-	HCHO	[182]
5.	**Graphitic carbon nitride**	Ag NPs	HCHO and VOCs	[184]
6.	**Graphitic carbon nitride**	Mo doped	CO_2	[185]
7.	**Carbon nitride nanosheets**	Zr-MOF	CO_2	[186]
8.	**Graphene oxide**	TiO_2	Methanol	[187]
9.	**CQDs**	TiO_2	Benzene, Toluene, and p-Xylene	[188]
10.	**Activated carbon**	Mn/TiO_2	Toluene	[189]
11.	**Activated carbon filters**	BiOI/Bi_2WO_6	Toluene	[190]
12.	**CQDs**	Bi_2WO_6	Acetone and Toluene	[191]
13.	**Multi-walled carbon nanotubes**	TiO_2	CO_2, NO_2	[194]

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14.	**Graphitic carbon nitride**	Ag_3PO_4	HCHO	[195]
15.	**Graphitic carbon nitride**	QDs decorated TiO_2	HCHO	[196]
16.	**$g\text{-}C_3N_4$**	MnO_2 and biochar	HCHO	[197]
17.	**Activated carbon filter**	CeO_2 and TiO_2	Toluene	[198]
18.	**Activated carbon fiber**	Cu- TiO_2	Benzene and Toluene	[199]
19.	**Graphene oxide**	Fluorine doped	Methanol	[200]
20.	**$g\text{-}C_3N_4$**	Bismuth NPs	HCHO	[201]

The hydroxyl radicals form dioxymethylene (DOM) and then convert DOM to formate ions ($HCOO^-$). $HCOO^-$ further decomposes into CO_2 leading to overall conversion efficiency of 46%. Similarly, Chen et al. revealed that UV-assisted photo-electrochemical catalysis integrated with microbial fuel cell (PEC-MFC) system for VOCs removal operates as follows: exoelectrogens at the anode metabolize organic substrates, generating electrons that flow through an external circuit to the cathode, producing electric energy [193]. Under UV light, photo-induced electrons in CeO_2/TiO_2 composites move from the conduction band of CeO_2 to TiO_2, reacting with O_2 to form superoxide radicals, while Ce^{4+} ions convert to Ce^{3+} and also produce superoxide radicals. Additionally, holes in TiO_2 oxidize water to produce $^{\cdot}OH$ radicals. These reactive species decompose pollutants into CO_2, H_2O or other small molecules. The enhanced photocatalytic activity of the CeO_2/TiO_2/ACF cathode is due to effective electron-hole pair management, the generation of superoxide radicals through Ce^{4+}/Ce^{3+} redox cycles and benefiting from ACF substrate's high conductivity and adsorption capacity.

4. CASE STUDIES AND PROBABLE INDUSTRIAL APPLICATION OF CBNS IN AIR PURIFICATION

CDs have emerged as a great technology in the realm of air purification because of their remarkable properties and versatility. Recent case studies have showcased CDs potential in air purification, illustrating their ability to efficiently degrade and remove a wide array of airborne pollutants via various methods like filtration, adsorption and photocatalytic oxidation. Zagorskis and Vaiškūnaitė [202] studied breakthroughs in biological air treatment leading to the development of filter systems that merge natural zeolite granules, foam cubes, and wood chips to create biofilters of enhanced efficiency and more lifespan of filter. Demonstrated that microorganisms, crucial for biological purification can also thrive in synthetic and inorganic biofilter beds for optimization of purification efficiency based on pollutant origin, concentration and filtration duration. For pollutants like acetone, toluene and butanol, the filter achieved a removal efficiency of up to 95% under initial concentrations of ~100 mg/m³. The better performance was observed with acetone and butanol due to their high solubility in water. Notably, increasing pollutant concentration results in decreased efficiency, concluding that lower concentrations have great purification performances in case when acetone concentrations rose from 103 to 305 mg/m³, the removal drops from 96% to 80%. Thus, integrating the biological and adsorption methods offers a more adaptable and productive solution for managing air quality.

In another study, Li et al. [203] introduced an advanced triboelectric air filtration system utilizing triboelectric nanogenerators to increase air purification by $PM_{2.5}$ and bacteria removal. This integrates industrial filter media such as filter cotton or sponge, with a layer of polytetrafluoroethylene and frictional electrification between these layers boots the air filtration by increasing the removal rate of PMs from 20% to 40%. In addition to this, it improves capture ability for harmful bacteria like *Staphylococcus aureus*. The system involves a self-activating mechanism that achieved a significant 99% removal of $PM_{2.5}$ in a cigarette-filled confined space within 30 minutes. This self-charging, powered by wind filtration technology offers a promising solution for outdoor air purification, setting a new standard for particulate removal and environmental pollution control.

With increasing global attention on air pollution and environmental sustainability, demand for natural gas vehicles and advanced technologies for flue-gas cleanup are on peak. To address these demands, formation of carbon-based adsorbents derived from waste tires has gained a prominence as a viable strategy. Brady et al. [204] in their work utilized tire waste for ACs via pyrolysis and steam activation methods with their significant properties. Tire-derived ACs are proving themselves as formidable contenders in methane adsorption that come impressively

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close to those of high-end commercial products like Calgon BPL, hitting about 90% of their performance. However, their storage capacity falls short by about 60%, primarily due to lower density of the tire char. Moreover, un-activated tire char itself strong performer particularly in SO_2 adsorption matches the ability of ACs used in Germany for incinerator flue-gas cleanup. Also, research focused on enhancing the performance of adsorbents by increasing packing density using pellatization that is compressing tire-activated carbons into pellets that target the betterment to 90 V/V_o and this is nearly half of the Gas Research Institute's ambitious target of 200 V/V_o. Therefore, the above demonstrated method not only mitigate the issue of solid waste because of tires but also led to more cost-effective production of carbon-based adsorbents for air pollution control.

Zakuciová et al. [205] in their study reveals that The Czech Republic is advancing new technologies for reduction of greenhouse gases from its coal-based power sector, specifically through post-combustion CO_2 capturing by ACs adsorption. A life cycle assessment (LCA) has been performed to evaluate the environmental impacts of this technology under Czech conditions, comparing a standard power unit with one equipped with CO_2 capture. The LCA highlights notable environmental improvements such as reduced climate change potential, terrestrial acidification and particulate matter formation. Along with identification of higher energy demands and fossil fuel depletion due to the continued dependence on coal in the Czech, it also includes a preliminary economic evaluation of the payback period for implementing the carbon capture system. Despite the carbon capture process itself has relatively low harmful environmental impacts as compared to the power plant, improving quality of coal and usage of other biomass alternatives is still a major issue. They concluded that integrating optimized carbon capture and utilization technologies could offer a practical solution for greenhouse gas emissions while balancing economic considerations.

Globally, humanity has confronted a historic challenge with the novel coronavirus SARS-CoV-2, which causes COVID-19. In the face of this unprecedented pandemic, researchers have been urgently investigating how the virus spreads to devise effective containment strategies [206-208]. Despite intense efforts, there are currently no proven methods to fully control its transmission. The relaxation of lockdowns has led to increased air pollution, which may impact virus spread by facilitating its attachment to airborne particles. Thakur et al. [209] summarizes graphene nanomaterials, with their impressive antimicrobial and antiviral properties, effective in combating COVID-19. These materials majorly known for their ability to disrupt viral and bacterial membranes through both physical and chemical mechanisms, offer promising solutions for reducing SARS-CoV-2 transmission. Their lightweight nature and ease of functionalization make them ideal for enhancing personal protective equipment such as face masks, gloves, and other fabrics thereby improving their effectiveness in controlling virus spread. Meanwhile, in polluted cities like Delhi, severe air pollution has worsened the spread of respiratory infections, including COVID-19. Graphene based face masks had high efficiency in filtering out $PM_{2.5}$ particles, achieving a 96.4% removal rate, effective protection against airborne pollutants. Despite this, the effectiveness of these masks is contingent upon widespread public adoption. Based on the above discussion, it can be inferred that graphene holds significant potential in controlling the spread of the SARS-CoV-2 virus. Similarly, according to research done by Estevan et al. [210] concluded that in contrast, data on graphene nanomaterials is less comprehensive, particularly regarding its toxicokinetics. To enhance their effectiveness, masks are coated with antimicrobial NPs such as silver and graphene. Silver NPs, mainly known for their antimicrobial properties, have been assessed and estimates that systemic exposure from wearing silver-coated masks ranges from 7.0×10^{-5} to 2.8×10^{-4} mg/kg bw/day, well below conservative safety thresholds (0.075 to 0.01 mg/kg bw/day), indicating that chronic exposure is considered safe. In addition to antimicrobial and antiviral properties, antibacterial properties of breath masks are of great significance for bacteria free air around. Hashmi et al. [211] suggested copper oxide (CuO) as an antibacterial agent due to its superior properties and cost-effectiveness compared to other metallic NPs like copper, gold and silver. Copper (II) oxide, a stable and hydrophilic oxide was used to produce nanofibers for masks. The CuO loaded polyacrylonitrile nanofibers demonstrated enhanced strength, with 1.00% CuO significantly increasing tensile strength to 8.43 MPa with high breathability, 50% cell viability after 120 hrs and improved air permeability. By integrating these nanofibers into air purification systems, they can significantly contribute to cleaner and safer environment in both residential and industrial environments.

6. CONCLUSION

In essence, this review converges to a complex field that involves utilization of harnessing atmospheric particulate materials (PMs) itself as precursor for synthesizing carbon-based nanomaterials (CBNs). Traditionally considered as hazardous pollutants, PMs presents valuable opportunity for converting waste into high-value carbon materials offering new avenues for environmental, industrial and medical applications. Their extensive optical and chemical properties seems to be responsible for their vast applications. It highlights in-depth analysis of diverse adsorption strategies and photocatalytic oxidation processes involving CBNs used up for advanced air purification technologies. Additionally, this research lightens up the significant role of CBNs synthesized from PMs in air pollution control, demonstrating their effective contribution to mitigate environmental pollution. This comprehensive study further underscores case studies that illustrate the practical applications of CBNs in real-world scenarios, showcasing their versatility in tackling environmental

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problems to sweeping extent. As with any development, there are pros and cons thus adverse challenges like safety concerns, slow progress in real-world applications and scalability have been identified and need to be settled. To overcome these challenges, the discussion focuses on diverse future research directions such as exploring field applications and advancing regeneration techniques with the goal of fostering a safer and cleaner environment.

5. CHALLENGES AND FUTURE PROSPECTIVE

CBNs such as carbon quantum dots, graphene, carbon nanotubes and activated carbon exhibit an array of exceptional properties that render them indispensable across a myriad of environmental applications. They feature a high surface area, exceptional mechanical strength, strong chemical properties and high solubility. Furthermore, their tunability and functionalization capabilities enhance their adsorption efficiency and its performance in varied conditions. Although a diverse array of CBNs is available for air purification, still there are some unresolved challenges and opportunities for enhancement and refinement. There are some challenges that need to be addressed:

Material functionalization and stability: Functionalizing CBNs can improve their performance but it may also introduce stability concerns or cause their effectiveness to wane over time.

Scalability: Transitioning from laboratory breakthroughs to large-scale industrial applications while preserving both performance and affordability can be a complex challenge.

Regeneration and longevity of materials: Regenerating CBNs is a sophisticated and energy demanding procedure. Frequent regeneration can cause material deterioration which may impair its durability and economic viability.

Synthesis and safety concerns: Ensuring synthesis with safety concerns can also be a challenging factor, especially when dealing with hazardous air pollutants. Among various synthetic approaches utilized for converting PMs to CBNs, acidic oxidation method is found to be the most prominent. Being a non-greener method, it can also produce health concerns.

Real world applications and testing: To verify laboratory results and evaluate the practical performance of materials in dynamic real-world conditions is also a demanding task. The future opportunities in this research area will be pursued through so perspectives outlined here which need to be addressed promptly.

Advanced material development: CBNs with other functional materials can be innovatively hybridized in such a way that boosts their efficiency ensuring that their stability remains intact.

Enhanced regeneration techniques: Designing materials that feature self-regenerating abilities or extended durability can overcome the regeneration difficulty.

Field applications: While a handful of real case studies exist, but they are relatively sparse. This presents an opportunity for further exploration and expansion to enrich the practical applications.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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