pollutants

Review

Exigency for the Control and Upgradation of Indoor Air Quality—Forefront Advancements Using Nanomaterials

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Abstract: Due to increasing health and environmental issues, indoor air quality (IAQ) has garnered much research attention with regard to incorporating advanced clean air technologies. Various physicochemical air treatments have been used to monitor, control, and manage air contaminants, such as monitoring devices (gas sensors and internet of things-based systems), filtration (mechanical and electrical), adsorption, UV disinfection, UV photocatalysts, a non-thermal plasma approach, air conditioning systems, and green technologies (green plants and algae). This article reviews presently viable technologies for cleaning indoor air and enhancing IAQ. However, regarding the integration of each technology, there are certain limitations to these methods, including the types of pollutants released. As a result, advanced nanomaterials have been applied to monitoring sensors, filtration and adsorption media, and UV photocatalysts to improve IAQ values. The most important nanomaterials used in this regard include polymeric nanofibrous membranes, nanoporous nanomaterials, nanocomposite hydrogels, polymer/nanocarbon nanocomposite, polymer/metal oxide nanocomposite, polymeric nanohybrids, etc. Accordingly, through the use of nanotechnology, optimal solutions linking IAQ regulation techniques to novel nanomaterials can be achieved to attain safe IAQ levels.

Keywords: indoor air quality; pollutants; filtration; sensors; UV disinfection; non-thermal plasma; nanomaterials; membranes; polymeric nanocomposite; nanohybrid

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1. Introduction

The indoor environmental conditions of buildings and houses greatly affect human health [1]. According to the World Health Organization (WHO), indoor air pollution may affect ~4–5 million people per year [2]. Most urban humans spend ~90% of their time indoors [3]. Therefore, the effect of indoor air environments on human health is obvious. Common sources of indoor air pollution include cooking, heating, smoking, garages, cleaning, electronic machines, outdoor air, and other human activities. Harmful indoor air pollutants include oxides of carbon, nitrogen, and sulfur; volatiles; particulates; aerosols; biological pollutants; and many more [4] (Figure 1). Indoor air pollution can lead to a range of physical illnesses, including cardiac, respiratory, nervous system, and even cancer-related diseases [5–7]. Consequently, indoor air quality (IAQ) monitoring, control, and management are considered important for preventing the related potential health risks [8]. The measurement of indoor pollutant concentration has been considered to be a crucial strategy for controlling and enhancing IAQ. It is also vital to determine the sources of indoor air pollution to ensure total eradication. The relationships between indoor pollutants and health risks and health effects have been found to be significant enough to justify adopting suitable remediation strategies.

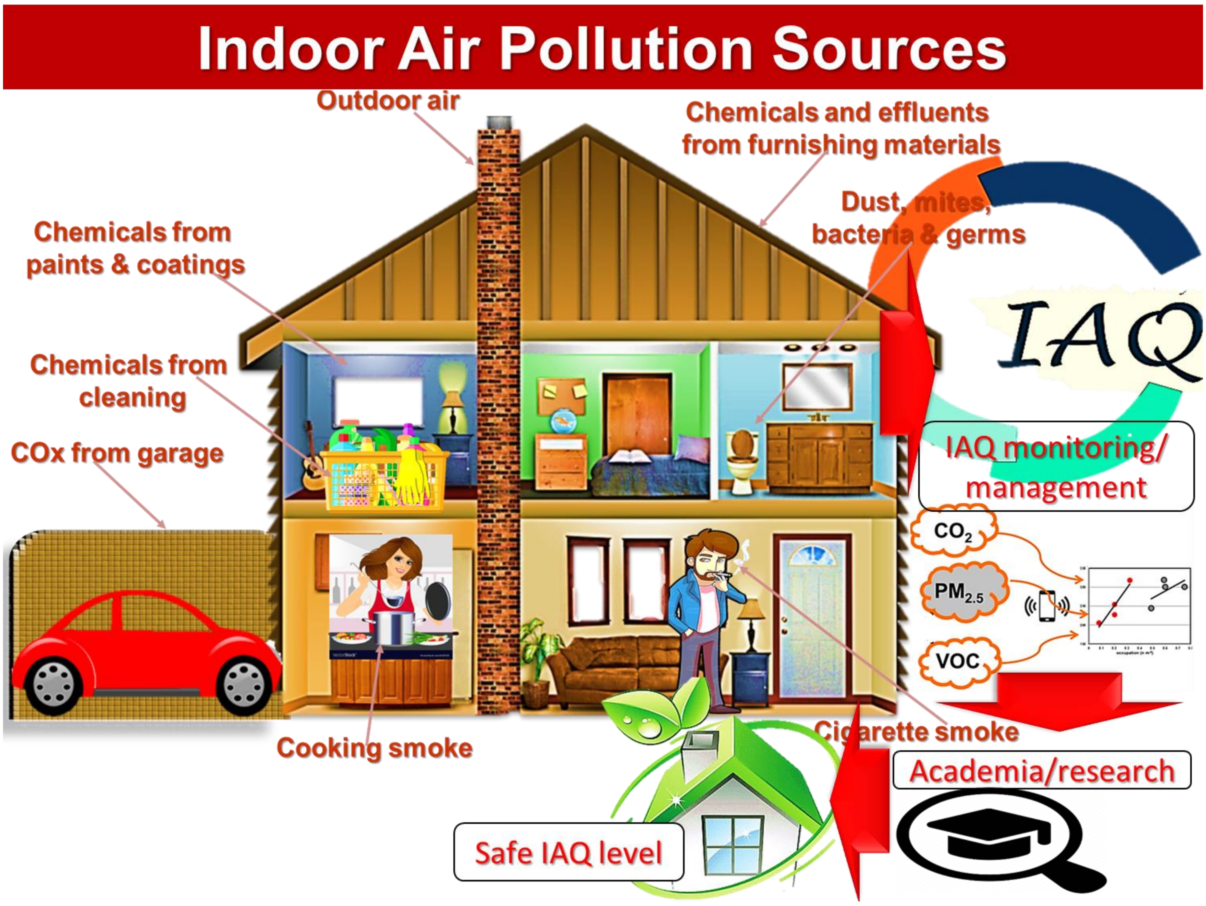

Figure 1. Common pollutants and sources in indoor air.

This paper presents a state-of-the-art review focusing on the essential indoor pollutants, the fundamentals of indispensable IAQ control and monitoring technologies, and the implementation of advanced nanomaterials in these technologies to develop a promising solution. To the best of our knowledge, such a comprehensive review linking indoor air control/management to advanced nanomaterials has not been reported before. Recent trending strategies for controlling and monitoring IAQ involve the use of an advanced nanomaterial in the sensing systems, filtration and adsorption media, and UV photocatalysts, as discussed in this review. The nanomaterials, nanofibrous membranes, nanoporous nanomaterials, hydrogels, nanohybrids, polymer/nanocarbon nanocomposite, polymer/metal oxide nanocomposite, etc. discussed here have been designed to reduce indoor pollutant concentrations for better IAQ. The future of IAQ control/monitoring relies on innovative, nanomaterial-based sensing systems, filtration/adsorption systems, and UV photocatalysts to eradicate indoor air pollutants. Thus, this novel review highlights the current situation regarding indoor pollutants, their health effects, and IAQ monitoring strategies. Consequently, the key pollutants, their health effects, and control techniques are here surveyed. Specifically, this article stresses the need for IAQ assessment, control, and monitoring technologies. Moreover, the involvement of academic/research institutes, government organizations, and stakeholders for long-term planned studies on indoor air pollution and linking indoor air control/management to appropriate policy interventions (as per WHO standards) are here found to be crucial.

2. Indoor Air Pollution: A Serious Threat to Human Health

2.1. Indoor Pollutants

IAQ is generally affected by factors such as outdoor air quality, building/construction materials, and human activity inside buildings [9]. Outdoor air pollutants directly influence IAQ due to the possible transfer of toxins from the outdoors to indoor atmosphere [10]. Outdoor pollutants result from industrial and transport activities [11]. Construction/building materials have been a source of indoor pollution due to the evolution of toxic organic compounds from paints, adhesives, coatings, poly(vinyl chloride) floor covers, rubber carpets, etc. [12]. Moreover, daily human activities (cooking, smoking, heating, cleaning, solvent uses, etc.) produce lots of indoor pollutants such as noxious gases, particulate matter, allergens, bacteria, viruses, insects, mites, etc. [13–15]. Major pollution-causing noxious gases include oxides of carbon (COx) such as carbon monoxide (CO) and carbon dioxide (CO_2); oxides of sulfur (SOx) such as sulfur dioxide (SO_2); oxides of nitrogen (NOx) as nitric oxide (NO), nitrogen dioxide (NO_2), particulate matter (PM), and volatile organic matter (PM) [16]. All indoor human activities and building materials are a rich source of PM, VOC, NOx, COx, SOx, ozone, Radon, etc. The ozone (O_3) is also a toxic indoor pollutant from computers, photocopying machines, printers, etc.

PM has varying size of <10 μm (large diameter coarse particles), fine particles of diameter <2.5 μm, and ultrafine particles of diameter <0.1 μm [17]. Inhalation of PM causes damaging effects to the lungs, heart, respiratory, and cardiovascular systems.

VOC consist of toxic gases and volatile chemicals from liquids or solids [18]. Formaldehyde is a toxic form of VOC emitted from building materials such as plywood, paints, coatings, coverings, etc. VOC are also penetrated in indoor environment from the outdoor air. The long term exposure to VOC can cause serious health risks like cancer [19].

NOx such as NO and NO_2 result from cooking, combustion, and other heating, and fire sources [20]. NO is a primary pollutant which is oxidized to form NO_2. NO_2 can easily react with water to produce nitrous acid (HONO)which is a harmful indoor contaminant. Common health risks of NOx are asthmatic reactions and lung infections [21].

SOx, especially SO_2 is a harmful indoor pollutant originating from outdoor air, cooking, smoking, heaters, and coal/wood burning [22]. Human exposure to SOx harms respiratory and cardiac functions causing asthmatic, pulmonary, and cardiovascular diseases.

COx such as CO emerges from indoor combustion (tobacco, cooking, gas heaters, stoves, furnaces, chimneys, etc.) and comes from outdoor air [23]. Even at low concentrations, CO can harm the cardiovascular, respiratory, and nervous systems [24].

Ozone is generally produced in the indoor environment due to photochemical reactions of VOC, COx, NOx, etc. [25]. It arises from outdoor sources, indoor photocopying, the and use of machines. O_3 can seriously affect lungs, DNA, and human organs causing asthmatic and respiratory diseases.

Radon is an indoor pollutant from building materials, soil, and tap water [26]. In indoor buildings, concentrations of radioactive radon (^{222}Rn) gas can attain harmful levels [27]. Lethal dose LD50 for radon inhalation is ~1.0 g causing toxic effects such as lung cancer and respiratory diseases [28].

Pesticides are used in an indoor environment to prevent pests, bacteria, fungi, insects, etc. Pesticides cause irritating effects on eyes, nose, and throat. Moreover, these chemicals cause damaging effects to the central nervous system, kidneys, and cancer risks [29].

Aerosols originated in indoor environments from various outdoor sources and also result from indoor gas-to-particle conversion of VOC [30]. Aerosols can be of different types such as carbonaceous aerosols, biological aerosols, and gas-to-particle aerosols. Carbonaceous aerosols originate from combustion, while biological aerosols are formed from animals, bacteria, and microorganisms. Aerosols frequently affect the human heart and brain-related systems.

Indoor biological pollutants include biological allergens (pets' saliva, dust, cockroaches, mites, pollens, etc.) and microorganisms (bacteria, viruses, fungi, etc.) [31]. Biological pollutants emerge from outdoor air. The most common human health effects include respiratory and allergic diseases.

To control and monitor all the above-mentioned pollutants, precise techniques need to be developed. To some extent, IAQ depends on indoor ventilation rates and related systems.

2.2. Health Effects–Short and Long Term

Indoor air pollutants may cause short-term or long-term health effects. Short-term exposure involves interaction with low concentrations of indoor pollutants or contact with indoor pollutants for a short span of time. Short-term exposure to indoor pollutants such as particulate matter, volatile organic compounds, NOx, COx, etc., does not cause serious health effects [32]. In some cases, short-term exposure to indoor pollutants may initiate headaches. Especially, NOx level of 28.97 $\mu g/m^3$, $PM_{2.5}$ concentration of 21.51 $\mu g/m^3$, PM_{10} level of 37.79-$\mu g/m^3$, and COx concentration of 1.15-ppm were found to cause headaches in indoor inhabitants [33]. On the other hand, long-term exposure to indoor air pollutants has their serious health effects. Usually, exposure to indoor pollutants for more than one month results in serious health risks [34]. Consequently, daily exposure or long term exposure may lead to cancer-causing effects [35]. Other important effects include sick building syndrome [36,37], building-related illness [38,39], pulmonary diseases [40,41], cardiovascular diseases [42–44], and many more. Table 1 illustrates common indoor pollutants and resulting hazardous effects on human health.

Table 1. Common indoor pollutants and their effects on human health.

Pollutant	Source	Health Influence	Ref
Particulate matter	- Outdoor environment - cigarette smoke - cooking, burning/candles, fireplaces - heaters - cleaning events	- Heat and lung diseases - amplified respiratory symptoms	[45–47]
VOCs	- Paints/varnishes/polishes and dyes - pesticides from wood furniture - adhesives/lubricants - tobacco use and smoking - perfumes and air fresheners - printers, etc.	- Headaches and nausea - irritation of nose/throat - impairment to the central nervous system - liver/kidney damage	[48,49]
NO_2	- Gas-fueled cooking - heating appliances	- Asthmatic reactions	[50,51]
O_3	- Outdoor sources - Photocopying	- Disinfecting devices - DNA damage - lung damage - asthma and decreased respiratory rate	[52,53]
SO_2	- Outdoor air - cooking stoves - fireplaces	- Impairment of respiratory function - asthma and chronic pulmonary disease - cardiovascular diseases	[54,55]

Table 1. *Cont.*

Pollutant	Source	Health Influence	Ref
COx	- Outdoor air - cooking stoves and fireplaces - tobacco smoke - gasoline powered gears	- Fatigue and chest pain - impaired vision - reduced brain function	[56–58]
Aerosol	- Tobacco smoke - cooking - cleaning	- Cardiovascular diseases - respiratory and lungs diseases - allergies	[59,60]
Radon	- Outdoor air - soil gas - tap water	- Lung cancer	[61]
Pesticides	- Outdoor air - insecticides, disinfectants, and herbicides - textiles and cushioned furniture	- Eye, nose, and throat irritation - damage to the central nervous system - kidney damage - cancer risk	[62,63]
Biological allergens	- House dust - pets - insects - pollens	- Respiratory infections—asthma - Allergies	[64]
Microorganism	- Bacteria and viruses from human, animals, and plants	- Infectious diseases such as fever - digestive problems - respiratory infections	[65,66]

According to literature reports, high indoor particulate matter PM_1, $PM_{2.5}$, and PM_{10} concentration of up to 2000–9000 μg/m^3 (mainly due to indoor cooking and heating activities) cause pulmonary infections, lungs diseases, and cancer risks [67,68]. Moreover, PM and CO_2 emissions due to tobacco smoke instigated coughing, sneezing, and eye irritation in indoor inhabitants [69]. Presence of indoor gaseous pollutants such as CO, NO_2, SO_2, O_3 was found to be associated with asthma risks and nervous system issues [70]. High indoor dust ingestion of ~8.79–34.39 ng/g, containing polychlorinated biphenyl concentrations, had serious health effects such as cancer risks and loss of indoor working productivity [71]. Indoor inhalation of flame retardants (up to concentrations of 128,000 ng.g^{-1}) revealed respiratory issues and loss of indoor working productivity [72]. Furthermore, high levels of indoor microflora and bacteria ~10,000–15,000 cfu m^{-3} caused respiratory and cancer risks [73,74].

3. Monitoring of Indoor Air Quality (IAQ)

Indoor air quality (IAQ) is defined as air value inside and around the buildings [75]. IAQ is important for health and coziness of building inhabitants. Harmful air pollutants (volatile organic compounds, particulate matter, and physical, chemicals, and biological aspects) at high concentration levels in indoor air cause negative health effects on human body.

An analysis of air quality level of south-east Asian countries (Pakistan, India, Nepal, Sri Lanka, Bangladesh, and Bhutan) has been carried out [76]. Comparative evaluation was performed for indoor pollutants such as PM_{10}, $PM_{2.5}$ and CO. WHO standards were considered for comparison. The WHO standards set for indoor PM_{10} level were 50 µg/m^3 and $PM_{2.5}$ was 25 µg/m^3. Air quality level (200–5000 µg/m^3) was attained much higher than the WHO standard value for safe IAQ [77]. Moreover, carbon monoxide level was found much higher (~29.4 ppm) than the WHO set standards (<5 ppm). The suggested reason was conventional indoor fuel burning sources, which affected >50% of indoor population. Consequently, employment of IAQ policies was found indispensable to safeguard public health in these countries [78]. Moreover, rising indoor pollutant levels pointed to increasing respiratory, nervous, and mortality rates in population [79].

Research, analysis, and monitoring for IAQ levels have arisen as a significant research field [80]. Purpose of supervising IAQ is to protect humans occupying non-industrial buildings from harmful pollutants. It is important to mention that IAQ assessments are found to be affected by indoor conditions such as temperature, light, humidity, air flow, etc. [81]. Initially, indoor pollutants have been controlled through adjusting indoor temperature and humidity. Figure 2 demonstrates a flow chart for steps involved in monitoring, control, and management of indoor air quality.

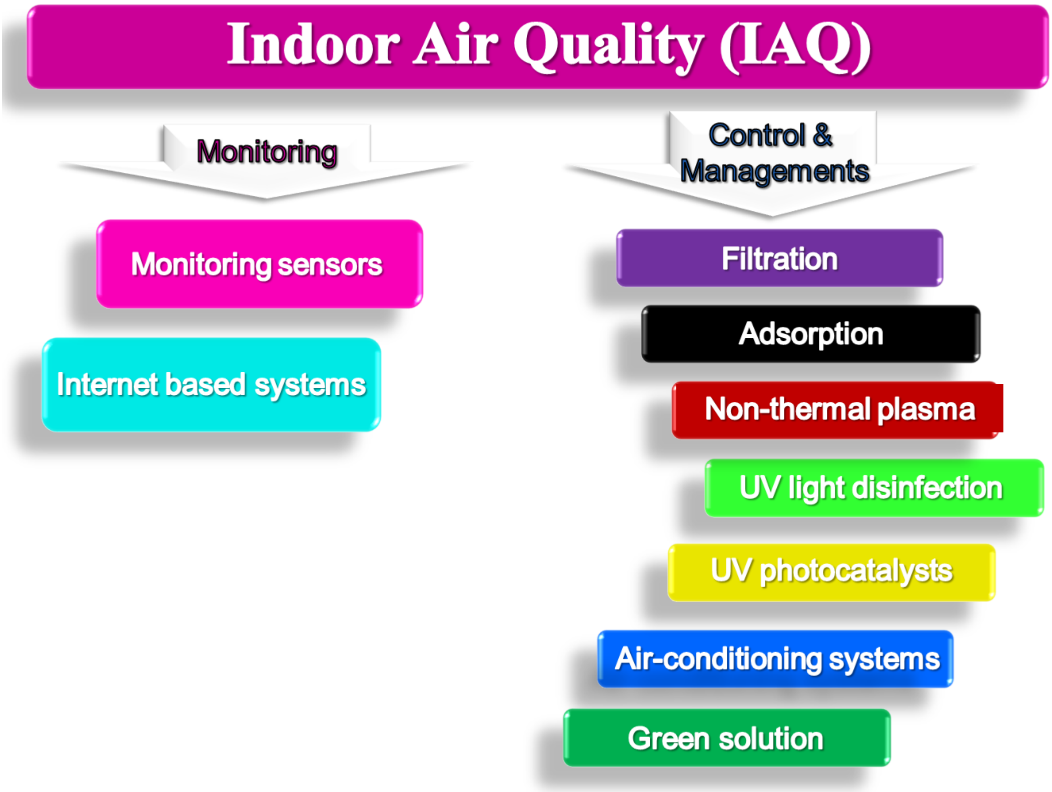

Figure 2. Indoor air quality—Monitoring, control, and management.

3.1. Materials Based IAQ Sensors

For IAQ monitoring systems, sensors have gained considerable research interest [82]. Initially, two-dimensional nanostructured materials have been invented for gas sensing [83]. Later research attempts focused zero-, one-, and three-dimensional nanostructured materials for developing IAQ monitoring sensors. These nanomaterials have been used to develop gas sensors, light sensors, humidity sensors, and temperature sensors. For IAQ monitoring systems, manifold phases of data acquisition, processing, storage, and analysis have been used [84]. Figure 3 shows a conceptual architecture of IAQ monitoring system. The data processing phase is accomplished at hardware as well as software level. The data acquired is sent for storage and processing. The software was used for enhancing data analysis and visualization. Accuracy of sensors has been achieved through calibrations and maintenance procedures. Consequently, development of novel low-cost sensors offers precise output data for advanced IAQ monitoring systems.

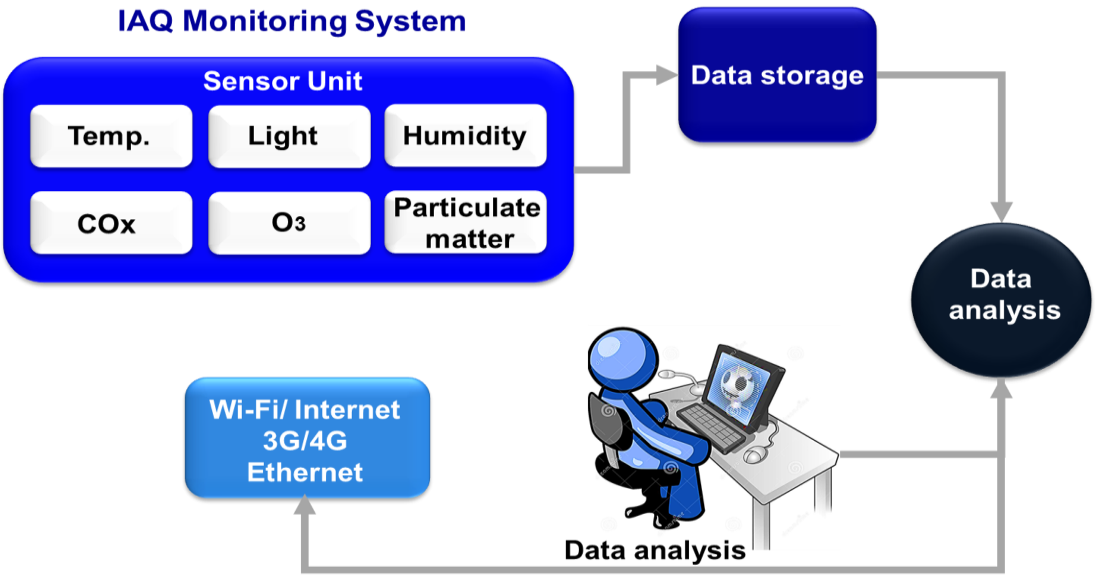

Figure 3. General conceptual architecture of IAQ monitoring system.

3.2. Advanced Technologies for IAQ Monitoring IAQ—Internet of Things (IoT)-Based Systems

Advanced techniques have been developed for IAQ monitoring [85]. Most prominently, internet of things (IoT)-based systems and wireless sensor networks have been developed. The IoT has been used as most popular technique for industrial revolution for IAQ monitoring [86]. Portable IoT devices have been effectively used for IAQ monitoring and control [87]. Recently, *electronic noses* or *e-noses* have been used as IoT devices for IAQ monitoring [88]. An *e-nose* is made up of multi-sensors arrays, processing units, digital software, and artificial neural networks. The *e-nose* has ability to monitor, detect, and discriminate various gaseous molecules [89]. Moreover, *e-noses* have low-cost and compactness for developing efficient IAQ monitoring systems [90]. The *e-noses* can sense numerous air pollutants such as CO, CO_2, NO_2, and particulate matter [91].

4. Control and Management of IAQ for Enhancing Air Value

Air purification technologies such as optimized ventilation systems have been developed for improving IAQ. Innovative technologies have been researched to filter/purify indoor air pollutants [92]. Here, the control of air pollution emission sources has been considered.

4.1. Filtration

For eradicating gaseous pollutants, two types of filtration processes have been used namely mechanical filtration and electronic filtration [93]. In this regard, carbon-based filters have been used in filtration systems. Mechanical filtration is a commonly used technology for removing particulate matter and noxious gases from indoor air [94,95]. In this filtration technique, fiber-based membrane media has been used. For efficient removal of pollutants from indoor air, fiber diameter, surface area, and membrane pore size have been considered important [96]. Here, high filtration efficiency was achieved depending upon size of diffusing particles and gas molecules. In electronic filtration systems, static electrical charge is applied to filter media for enhancing removal of noxious gases/particle [93,97]. Electrically linked air-cleaning devices have been successfully used for air purification. Electronic filters of two types have been used i.e., electrostatic precipitators and ion generator/ionizers. Efficiency of electrostatic filtration systems is high, however, these techniques may cause health effects [98]. Electrostatic precipitators produce negative air ions and hazardous charged particles affecting the cardiorespiratory functions [99]. Moreover, clogging of these filters has been observed through repeated use [100].

4.2. Adsorption Technologies

Adsorption means capturing air contaminants or impurities on adsorbent surfaces [101]. For controlling IAQ, adsorption of noxious gases, volatile organic compounds, harmful particles, and gaseous pollutants has been examined. Effective adsorbent materials investigated here include activated carbon, silica gel, zeolites, clays, and polymers [102]. Activated carbon and zeolites have large surface area and reported for high adsorption capacity [103]. The activated carbon has microporous structure for adsorbing high molecular weight volatiles [104]. Adsorbent materials can be easily applied in buildings without using extra energy sources and having no issues of byproduct development [105]. Passive removal materials have been used as common adsorbents for cleaning indoor environments [106,107]. Based on adsorption mechanisms, passive removal materials have been categorized as *(i)* sorptive materials [108] and *(ii)* photocatalytic oxidation materials [109]. For controlling IAQ, passive removal materials have been comprehensively explored in literature [110].

4.3. Non-Thermal Plasma (NTP) Technologies

Non-thermal plasma (NTP) methods have been established for controlling and enhancing IAQ [111,112]. In NTP techniques, quasi-neutral environment with ions, electrons, radicals, UV photons, etc. have been generated [113]. Non-thermal discharge plasma methods have been adopted for eliminating corona discharge, COx, NOx, SOx, and volatile compounds from indoor air [114]. Similar to electrostatic precipitators, NTP method has drawbacks of producing secondary harmful pollutants (such as CO, NOx, formaldehyde, etc.), humidity effects, and poor energy efficiency [115]. These disadvantages have restricted applications of NTP technologies in indoor air purification systems.

4.4. UV Light Disinfection Systems

UV light disinfection system is a simple air decontamination technique [116]. Using UV light disinfection systems reduced microorganisms levels in indoor air [117]. The microorganisms are disinfected through covalent bond cleavage resulting in C, H, O and N of nucleotide chains [118]. Using UV light disinfection systems reveal better building ventilation avoiding health problems caused by microorganisms such as allergies and respiratory infections [119,120]. This technology needs to be further explored to broaden its perspectives for efficient air pollutant removal.

4.5. UV Photocatalytic Oxidation

UV photocatalytic oxidation is emerged as an interesting air purification technology [121]. UV photocatalysts have been used for treating adsorbed gases and biological particles. Most commonly used UV photocatalysts include TiO_2, ZnO, WO_3, and iron and other metal oxides for controlling IAQ levels [122,123]. Research attempts are observed for designing UV photocatalysts nanomaterials for improving oxidation efficiency and pollutant removal [124]. UV photocatalytic degradation of indoor gaseous pollutants, particulates, and biological pollutants have been reported [125]. Consequently, UV photocatalysts are found effective to attain clean indoor environment and enhancing IAQ [126]. According to literature, using TiO_2 based UV photocatalytic resulted in 50% reduction in NOx and 5–54% decrease in aromatic compounds (benzene, toluene, ethylbenzene, xylene) levels in indoor air [127].

4.6. Air-Conditioning (AC) Systems

Numerous AC systems have been reported for enhancing IAQ and indoor thermal comfort for indoor inhabitants [128–130]. AC systems have independent control of temperature and humidity for purifying indoor environment [131,132], outdoor air systems [133,134], and cooling ceiling and displacement ventilation systems [135,136]. The indoor air ventilation has been considered important for enhancing IAQ.

4.7. Green Solution to IAQ

4.7.1. Green Plants

The indoor green plants offer benefits of generating indoor oxygen, humidity, and natural ventilation system [137]. Using indoor green plants produce positive health effects by reducing stress levels and by improving work performance. Potential of green plants for cleansing and remediating indoor atmosphere has been established. According to studies, the indoor green plants have been used for air purification against SARS-CoV-2 (causing COVID-19). Mechanism of air purification relies on green plants capabilities for absorbing or degrading airborne pollutants. The green plants have ability to remove CO_2 through photosynthesis process and degrade PM and VOC through metabolic action of rhizospheric microbes [138]. The indoor plants species such as Aloe vera, *Chlorophytum comosum*, *Epipremnum aureum*, *Lagerstroemia macrocarpa*, *Dracaena sanderiana*, etc. have been studied [139].

4.7.2. Microalgae in Air Purification

Microalgaes (prokaryotic/eukaryotic microorganisms) are efficient photosynthetic organisms. It has high biomass yield and low nutrients need to grow in soil, seawater, freshwater, and even in harsh environmental conditions [140]. Microalgae has been used for improving IAQ through indoor oxygen production, CO_2 capture, and pollutants remediation. Biomass produced from microalgae can be transformed to chemicals/biofuels such as biohydrogen, biodiesel, biohydrocarbons, etc., for attaining ecological and economic values [141,142]. Figure 4 displays microalgae system to convert CO_2 to O_2 during photosynthesis and metabolism activities [143]. Using microalgae systems, indoor ventilation has been enhanced.

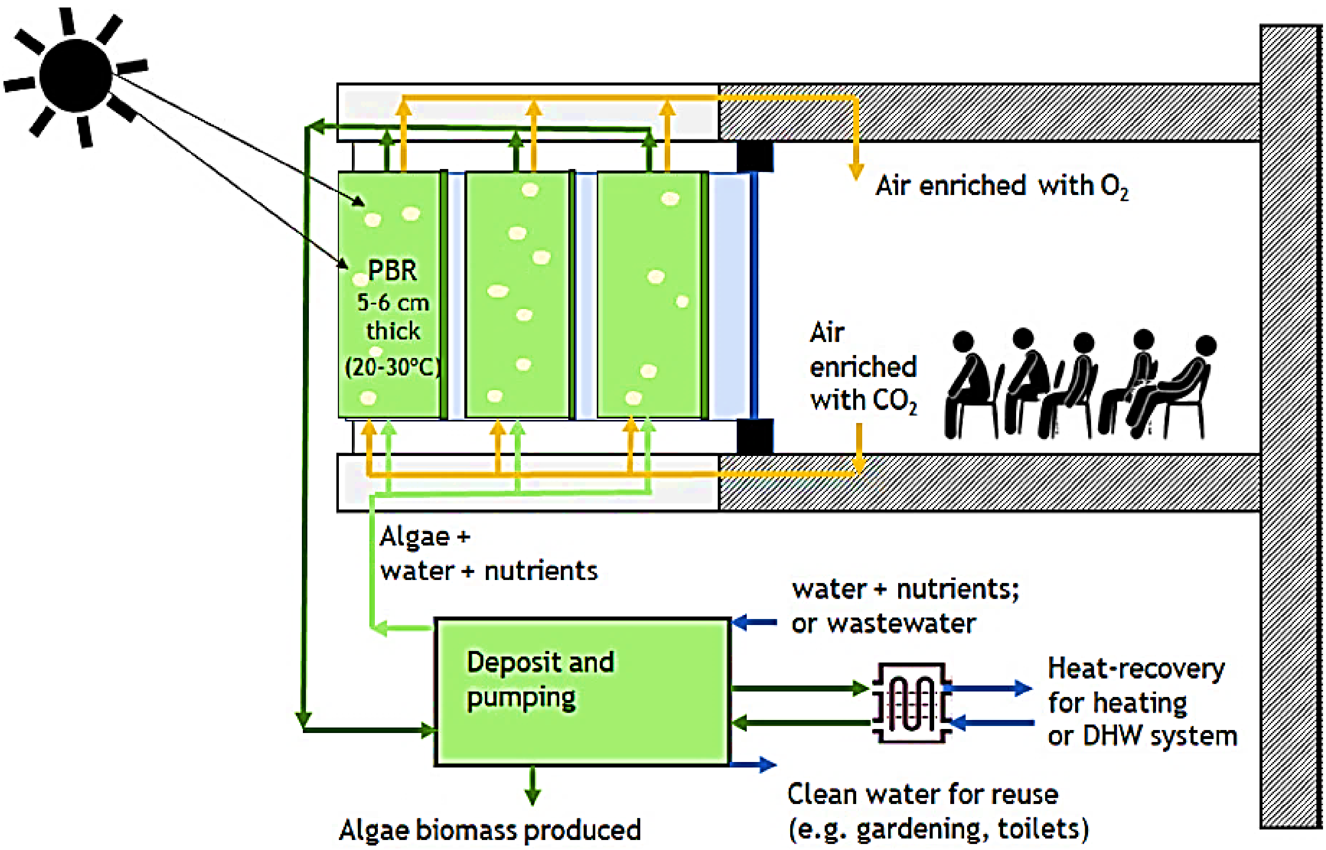

Figure 4. Microalgae cultivation system integrated into a building for indoor air treatment [144]. PBR = photobioreactor. Reproduced with permission from MDPI.

5. Use of Advanced Nanomaterials for Enhancing IAQ

Figure 5 expresses the use of nanomaterials for IAQ control/management systems. Basically, advanced nanomaterials (nanocomposites, carbon-based material, polymeric nanocomposites, nanohybrids, etc.) have been applied in the monitoring sensors, filtration systems, adsorption systems, and UV photocatalysts. IAQ techniques have efficiently clean the indoor air [145–147]. In Asian countries, the filters have been used to filter the dust from indoor air [148]. Moreover, the indoor adsorption systems have been used to remove the dust from air [149]. The indoor organochlorine pesticides concentration ~7.53–1272.87 ng/g was removed using filtration systems [150]. Removing indoor dust, PM, and gaseous pollutants have prevented the related lifetime cancer risks [151–153]. IAQ controlling systems have been used to protect indoor pollution in residential buildings, schools, and offices. Designing advanced equipment for enhancing IAQ can prevent indoor pollution issues by improving air quality [154].

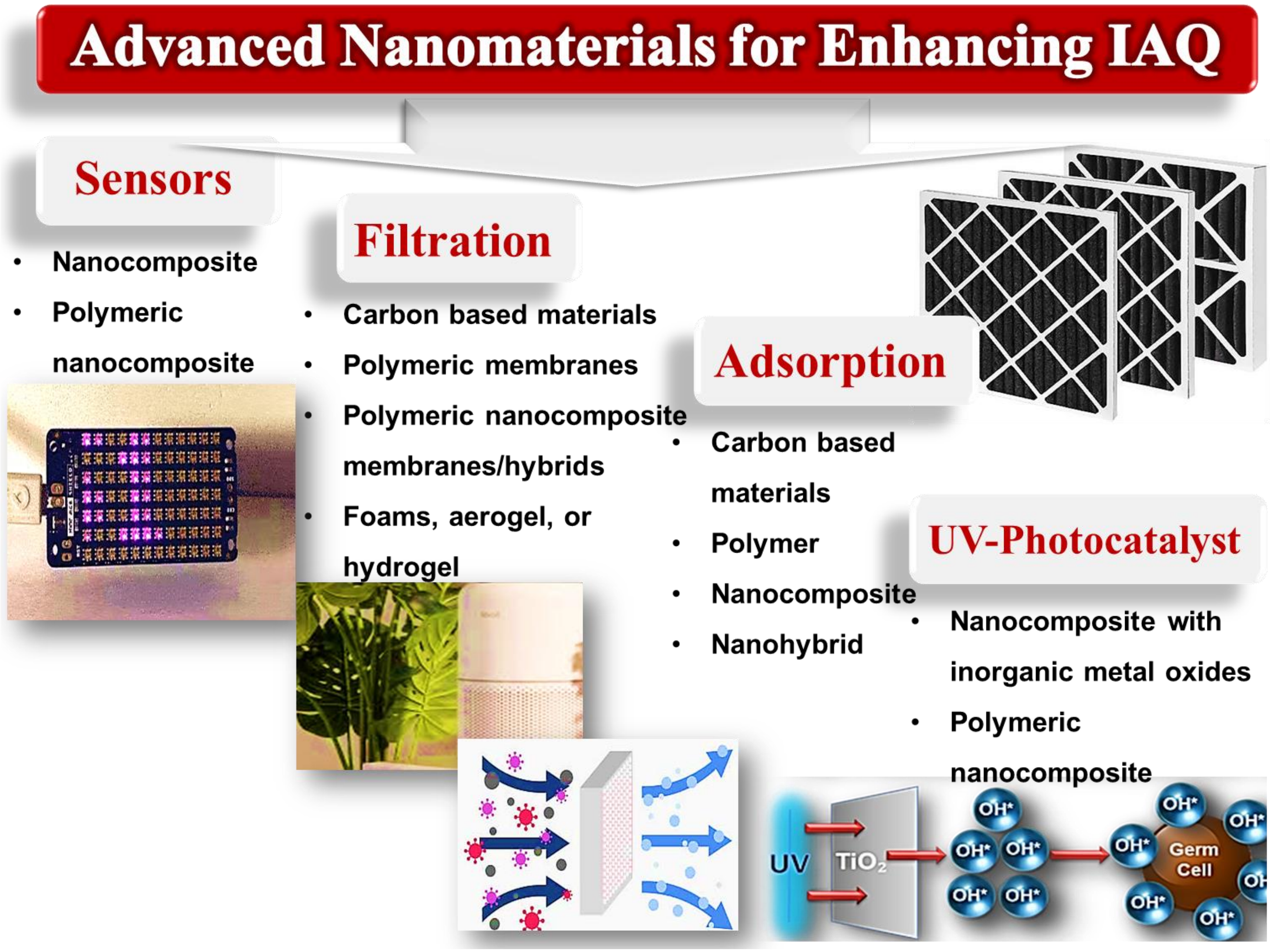

Figure 5. Advanced nanomaterials for enhancing IAQ.

5.1. In Monitoring Sensors

Gaseous contaminants such as COx, NOx, SOx, VOC, etc. from industries, automobiles, urbanization, households, and human activities are continuously contaminating our global ecosystems [155]. The WHO has reported human organs and systems (respiratory, immune, and nervous system) damages related to environmental contaminants [156]. As a result, there are increasing global demands for modern IAQ controlling and monitoring strategies [157]. The commercial sensors have low detection limits and poor selectivity for IAQ monitoring [158]. Here, the advanced nanomaterials have been used to develop hightech sensors [159]. The air contamination sensing strategies are mentioned in Figure 6 [160]. However, high costs, sophisticated designs, and time-consuming functioning have limited the use of sensors. Organic and inorganic nanomaterials have been reported for designing advanced sensors.

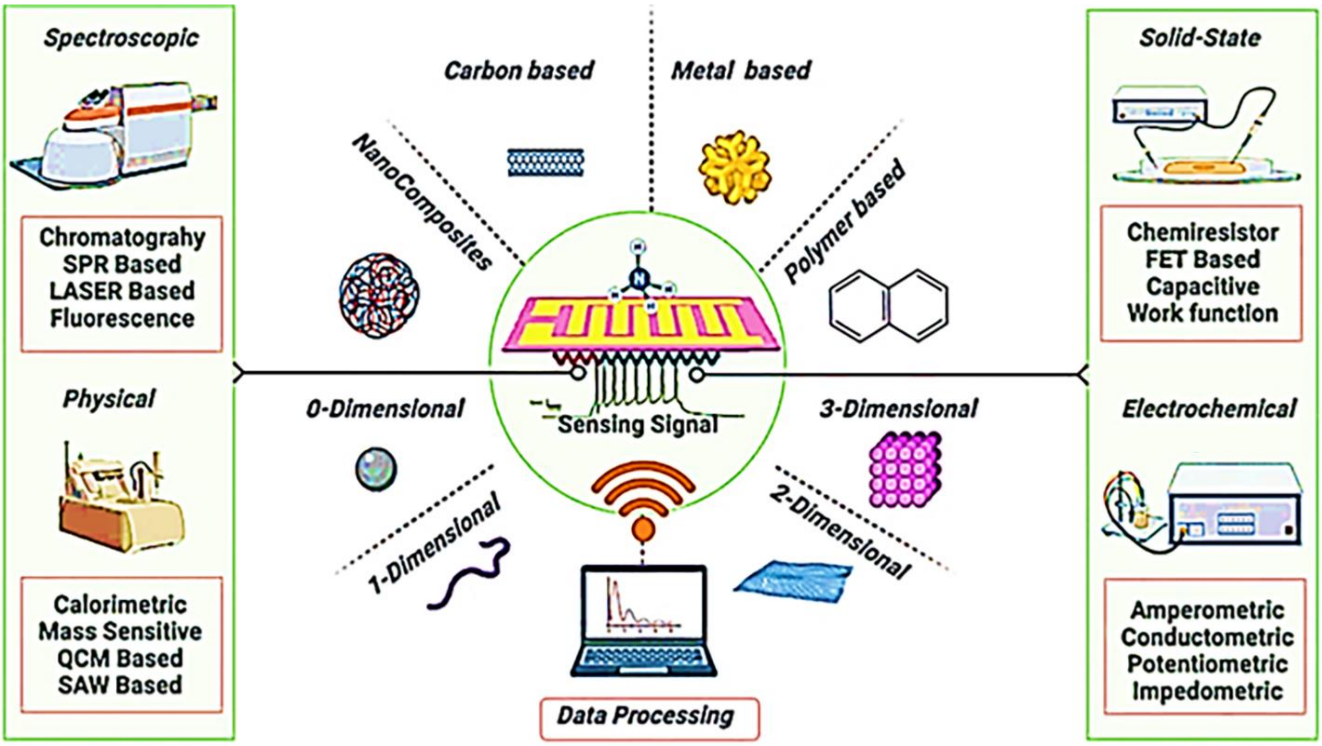

Figure 6. Schematic of various air contaminant sensing strategies depending upon nature of transducing signals and diversified sensing materials with different dimensions for air monitoring and detection [160]. Reproduced with permission from Wiley.

Gas sensors were developed using metal oxides filled polymeric nanocomposites. Onthath et al. [161] designed a novel VOC gas sensing setup (Figure 7). For designing sensor, carbon nanotube/copper oxide nanocomposites were prepared through sol gel method. The sensors exhibited high sensitivity to detect VOC such as benzene. Benzene was detected at low concentration of 5 ppm. Chougule et al. [162] prepared sensors using polypyrrole and zinc oxide nanoparticles. In polymer matrix, nanofiller was introduced in 10–50 wt.% contents. The polypyrrole/zinc oxide nanocomposite was used to detect NO_2 at low concentration of 10 ppm (Figure 8).

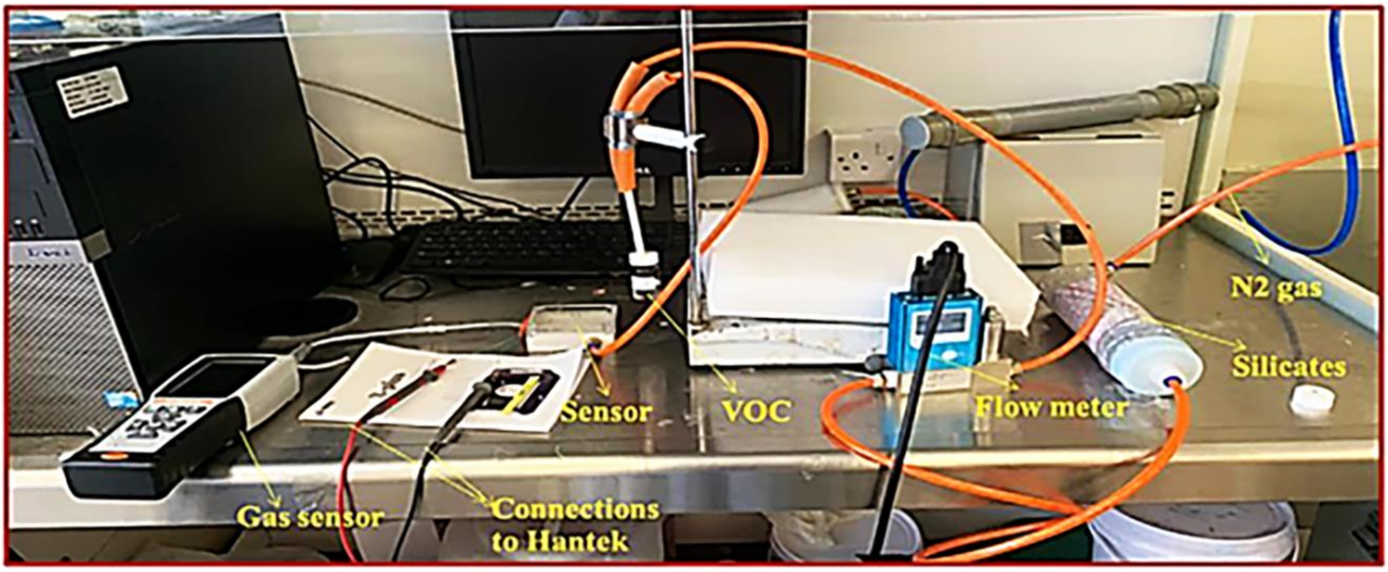

Figure 7. Schematic diagram of volatile organic compound (VOC) gas sensing setup [161]. Reproduced with permission from Wiley.

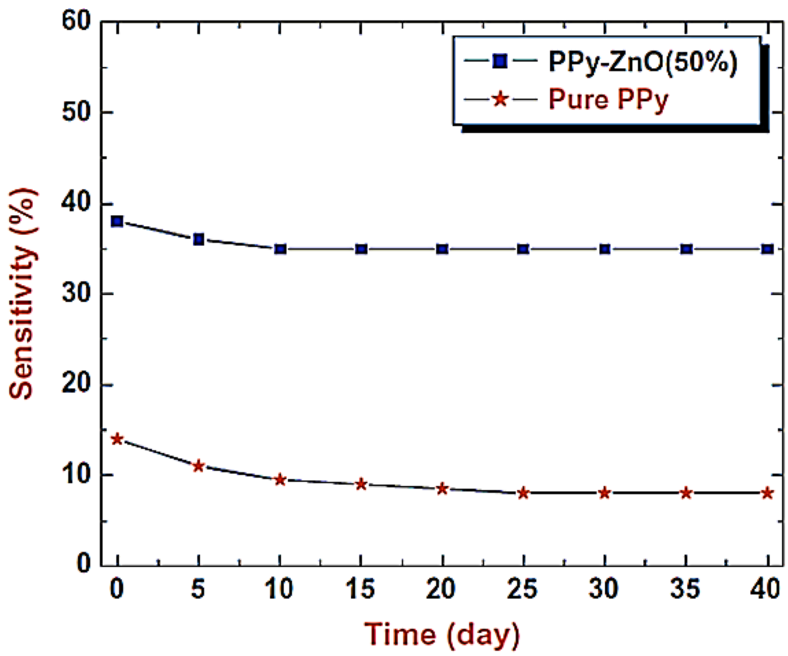

Figure 8. Sensitivity of neat polypyrrole (PPy) and polypyrrole/zinc oxide (PPy-ZnO) (50%) sensors [162]. Reproduced with permission from Elsevier.

Maximum NO_2 sensitivity of nanocomposite (100 ppm at room temperature) was~38% higher than neat polypyrrole. Sensing mechanism of p-n junction formation was observed for polypyrrole/zinc oxide nanocomposites. Gas sensors were prepared using graphene and graphene derivative nanomaterials. Comparative gas sensing performance of polymer/graphene nanocomposites is illustrated in Table 2. Sensor designs, synthesis techniques, and desired gas pollutants are discussed here.

Table 2. Gas sensors based on polymer/graphene oxide nanocomposites with polymeric materials.

Materials for Sensors	Synthesis Methods	Target Gases	Concentration Range	Sensitivity	Ref.
Polyaniline/graphene oxide nanocomposite	Layer by layer method	RH	~0–97% RH	~20.0%	[163]
Polyaniline/graphene oxide/tin oxide nanocomposite	In situ polymerization	H2S	~50 ppb to 10 ppm	~76.3%	[164]
Polypyrrole/reduced graphene oxide nanocomposite	In situ oxidative polymerization	NH3	~3–500 ppm	~34.7%	[165]
Polypyrrole/reduced graphene oxide/copper nanoparticle nanocomposite	In situ chemical polymerization	NH3	~10–150 ppm	~12.4%	[166]
Poly(3,4-ethylenedioxythiophene)/reduced graphene oxide nanocomposite	In situ polymerization	NO_2	~500 ppb—20 ppm	~41.7%	[167]
Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate/graphene oxide nanocomposite	Solution processing	NH3	~1–1000 ppm	~100	[168]
Poly(diallyldimethyl-ammonium chloride)/graphene nanocomposite	Layer by layer method; self-assembly	RH	~11–97% RH	~97%	[169]

5.2. Filtration and Adsorption Media

The indoor gaseous pollutants and PM continuously affect human health [5]. Filtration is used as an effective method to maintain safe IAQ level [170]. In air filters, specific surface area, hydrophilicity, mechanical stability, recyclability, and filtration efficiency are important for IAQ level. In this concern, polymers, nanocomposites, and nonfibrous nanomaterials have been used for indoor air filtration systems [171]. Conventional polymer (polyethylene, polypropylene, etc.) based air filters have low specific surface areas and affinity for PM and gaseous molecules [172]. In synthetic or natural polymeric nanocomposites, nanofillers such as nanocarbons, inorganic nanoparticles, and metal oxides have been used for attaining high filtration efficiency [173,174]. Table 3 shows few commonly used materials for filtration media for maintaining IAQ levels. Filtration mechanisms involve diffusion, interception, and gravity effects for removing PM, VOC, or other noxious gases from indoor air [175,176]. Electrostatic interactions of pollutants or PM particles with membranes (under electrical field) enhance their filtration efficiency [177].

Table 3. General materials for filtration media for IAQ.

Material	Two-Dimensional Material	Three-Dimensional Material
- Polymer - Carbonaceous material	Papers	Foam or sponges
- Polymer	Fabrics	Hydrogels
- Polymer - Polymeric nanocomposite	Fiber nets	Sponge-polymer networks
- Carbonaceous material - Polymeric nanocomposite	Meshes	Sponge-paper layered structure

Carbon-based materials possess high specific surface areas leading to high filtration capacity [178]. Carbon nanotube has a high surface area and small diameter for increasing the filtration efficiency of air filters [179].

Graphene or graphene oxide aerogel/foam nanomaterials have been developed [180]. Resulting graphene-based aerogels (formed by freeze drying method) have large specific surface area (1019 m^2/g) [181] and high $PM_{2.5}$ and PM_{10} filtration efficiency ~99–100% [182].

Fiber-based air filtration media have been reported [183]. Electrospinning method was used to form polymer fibers [184]. The polymeric fibers have high surface-to-volume ratio, flexibility, and chemical and mechanical properties [185]. Common polymers used in air filters include polyacrylonitrile [186], poly(methyl methacrylate) [187], poly(vinyl pyrrolidone) [188], poly(vinylidene fluoride) [189], nylon [190], polyimide [191], chitosan [192], etc. The resulting polymeric nanofibrous membranes have a high filtration efficiency of 99.98% for PM removal.

Chitosan or cellulose-based green air filters for IAQ have been reported [193,194]. Kaang et al. [195] produced wastepaper-based cylindrical hollow air filter (CHAF). Figure 9 shows a schematic of an air filtration system having CHAF, flow meter, and PM detectors. Structures of numerous polymers used with chitosan are shown in Figure 9. Chitosan has higher polarity than blended polymer-based CHAF promoting air filtration. $PM_{2.5}$ having size of 2.5 μm and a concentration of 644,000 $\mu g/m^3$ were filtered by these membranes. The diameter of CHAF fibers was 1–2 mm. Thus, CHAF has high removal efficiency for $PM_{2.5}$ (~99.12%).

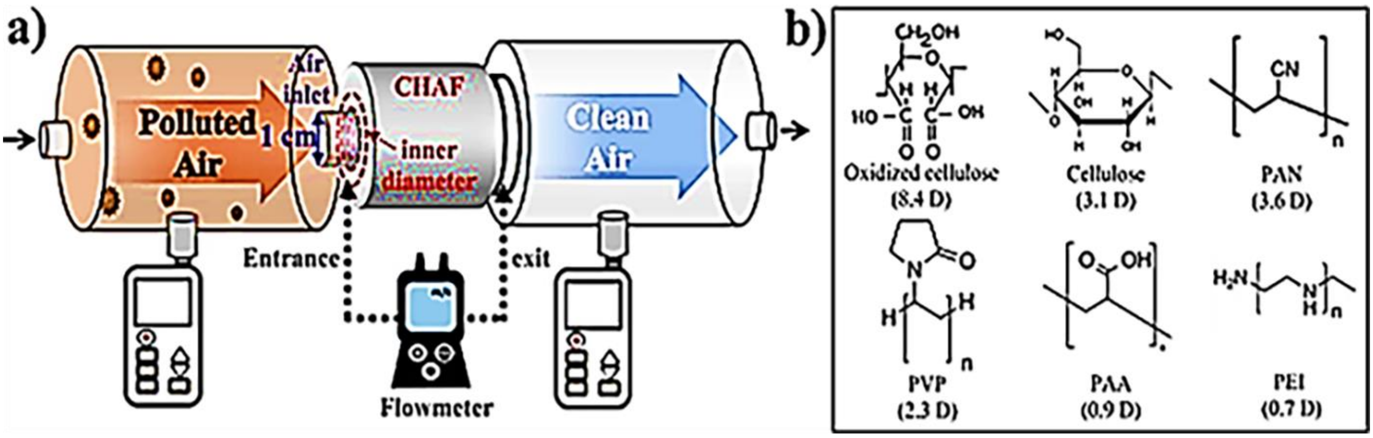

Figure 9. (**a**) Schematic of an air filtration system equipped with cylindrical hollow air filter (CHAF), flow meter, and PM detectors; (**b**) Structural formulas and dipole moments of various polymers [195]. Reproduced with permission from ACS.

Non-woven fabric membranes have been used for IAQ monitoring [196]. Wang et al. [197] prepared halloysite nanotubes@chitosan/polyvinyl alcohol/non-woven fabric hybrid membrane. Figure 10 demonstrates the fabrication process of filtration membranes. Uniform hierarchical porous air filters were prepared through the dip coating method. Fibrous composite membranes have a pore size of 27.5 μm and a porosity of 89.8%. Filtration efficiency for $PM_{2.5}$ was found high i.e., ~96.8%. Moreover, membranes have high antibacterial activity for *E. coli* and *S. aureus* bacterial strains.

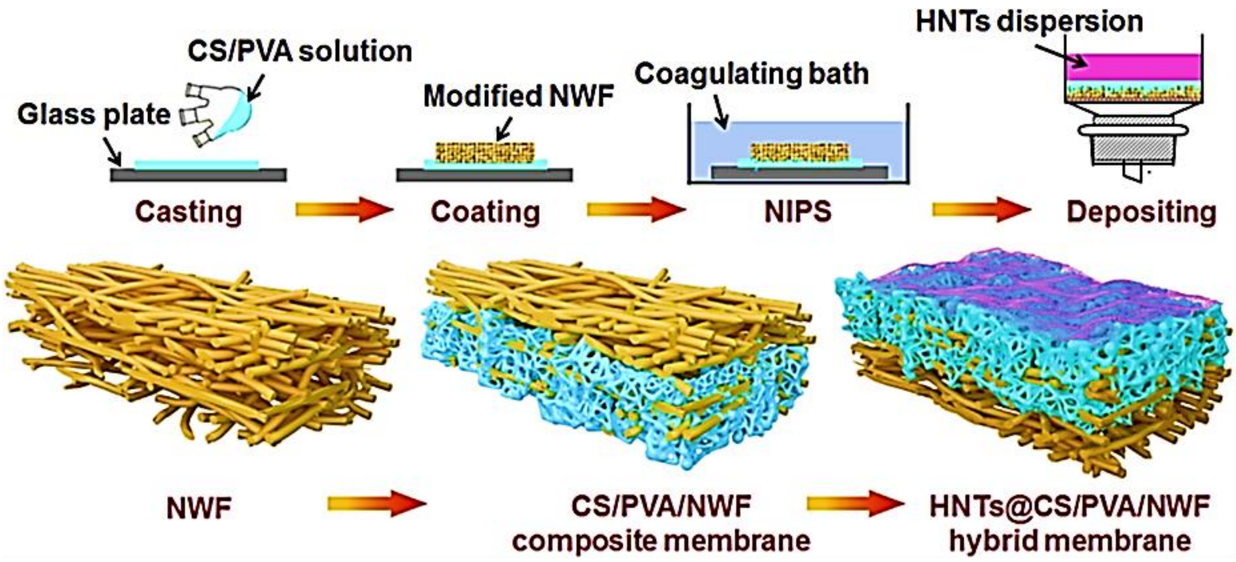

Figure 10. Schematic diagram for fabrication of HNTs@CS/PVA/NWF membranes [197]. NIPS = non-solvent induced phase separation; NWF = non-woven fabric; CS/PVA/NWF = chitosan/poly(vinyl alcohol)/non-woven fabric; HNTs@CS/PVA/NWF = halloysite nanotubes@chitosan/poly(vinyl alcohol)/non-woven fabric. Reproduced with permission from Elsevier.

Polymeric membranes and polymeric nanocomposite membranes have been effectively applied in air filters [198]. Polyacrylonitrile nanofiber-based air filters have been reported. Huang et al. [199] designed polyacrylonitrile nanofiber-based electrospun nanofibrous membranes for removing very fine indoor PM and preventing their lethal health effects. The diameter of polyacrylonitrile nanofiber was ~300 nm enhancing PM filtration efficiency up to >99% for a safe IAQ level [200]. Here, efficient removal of PM2.5 (particle size < 2.5 μm) was achieved. Su et al. [201] prepared polyacrylonitrile nanofiber and TiO_2 derived electrospun nanocomposite membranes. The nanoporous membranes have an average pore size of 2.7–4.6 μm. Hierarchical nanosporous membranes have enhanced filtration efficiency of ~99–100 for $PM_{2.5}$ with particle size < 2.5 μm. Hence, a safe IAQ level was attained [202]. Aydin-Aytekin et al. [203] developed polyamide 6/nanoclay/TiO_2 derived electrospun nanofibrous membranes for maintaining IAQ. The nanofiber diameter was ~75.8–135.9 nm for filtration of VOC indoor pollutants. The membranes have an air permeability of 119.9–309.4 g/m^2h. VOC removal efficacy of nanofibrous membranes was increased up to 44%, with increasing nanofiller loading (0 to 0.5 wt.%). Thus, IAQ was achieved through VOC removal [204]. Purwar et al. [205] designed the poly(vinyl alcohol)/Cloisite nanoclay-based electrospun nanofibrous membranes for maintaining IAQ. The diameter of electrospun nanofiber was in the range of 300–400 nm. The poly(vinyl alcohol)/Cloisite nanoclay membranes with 0.75% nanoclay were found promising for removing indoor $PM_{2.5}$ (up to 90–100%). In this way, 100% PM removal ensures a safe IAQ level for a healthy indoor environment [206]. Li et al. [207] developed poly(vinyl alcohol)/silver nanoparticle-based electrospun membranes. The poly(vinyl alcohol) matrix was grafted with 3,3′,4,4′-benzophenone tetracarboxylic acid to form electrospun membranes. Scheme for membrane formation is illustrated in Figure 11. The nanocomposite membranes were used for maintaining IAQ through the filtration of reactive oxygen species such as OH· radical and H_2O_2. Moreover, nanocomposite membranes have antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*. The 1×10^6 cfu aerosol with bacterial strains was filtered. Filtration efficiencies were quite high i.e., ~99.98%. Removal of aerosol and bacteria from indoor air resulted in a safe IAQ level.

Recently, Bonfim et. al. [208] produced polyethylene terephthalate-based electrospun nanofibrous membranes. In membranes, the fiber diameter was ~1.27 μm. The membranes had high porosity of 96% and permeability of 4.4×10^{-8} m^2. PM and aerosol nanoparticles including bacteria, fungi, and virus of ~100 nm were removed using these membranes. Figure 12 shows the increasing efficiency of polyethylene terephthalate-based electrospun nanofibrous membranes with increasing particle diameter (70–100 nm). Minimal efficiency was observed for a particle size of 20 nm. Nanofibrous polyethylene terephthalate membranes were found effective to clean the indoor air of hospitals and food industries. Thus, reported nanocomposite membranes are found promising for maintaining high IAQ standards, due to structural stability, reusability, and filtration efficiency.

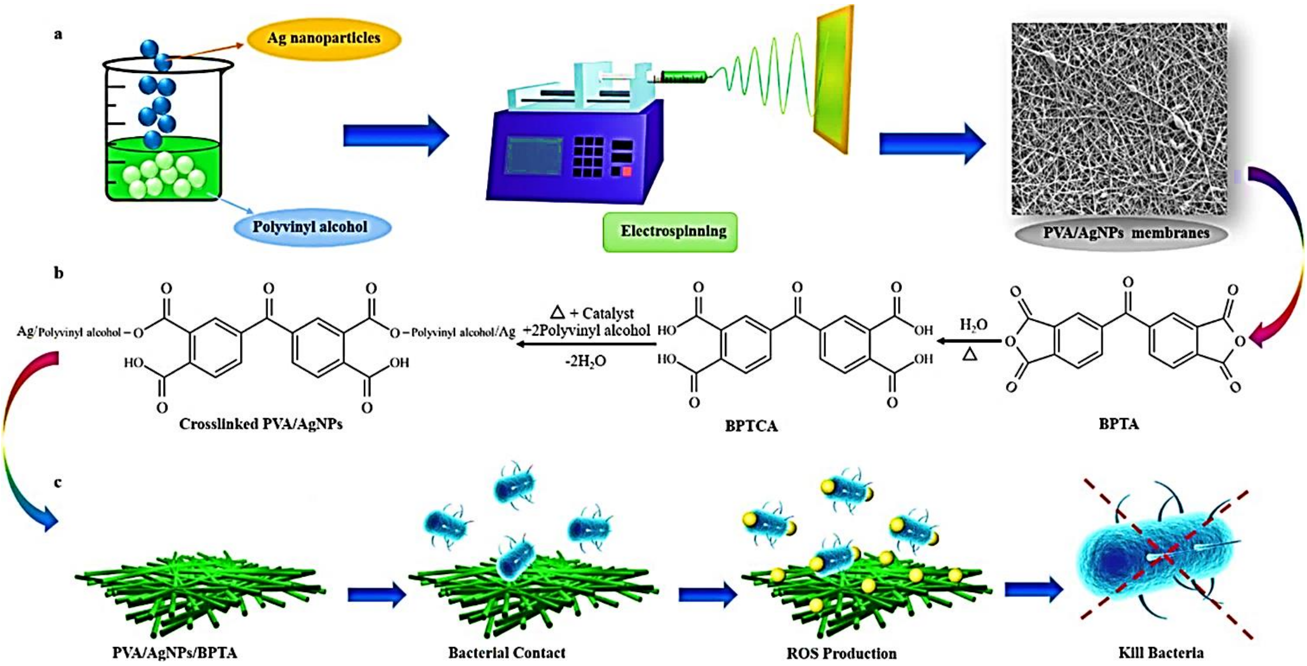

Figure 11. Polymer poly(vinyl alcohol)/silver nanoparticle-based nanocomposite membrane for air filtration [207]. PVA/AgNP = poly(vinyl alcohol)/silver nanoparticle; BPTA = 3,3′,4,4′-benzophenone tetracarboxylic acid; PVA/AgNP/BPTA = poly(vinyl alcohol)/silver nanoparticle/3,3′,4,4′-benzophenone tetracarboxylic acid; ROS = reactive oxygen species. Reproduced with permission from Elsevier.

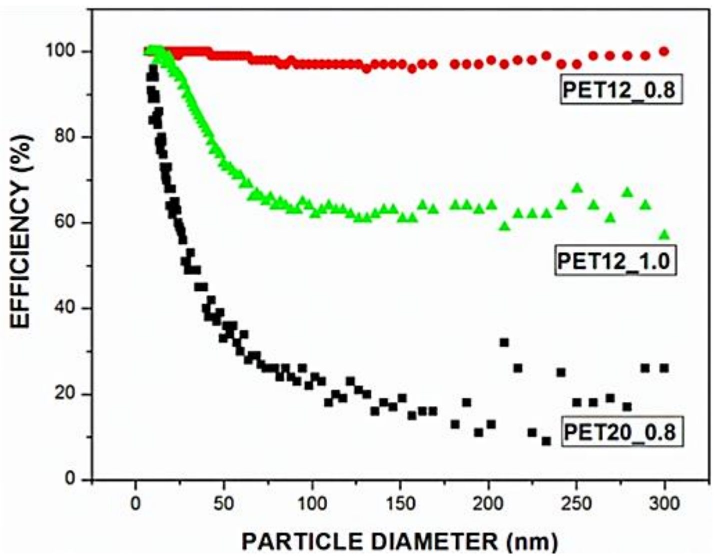

Figure 12. Fractional efficiency curves for samples with filtration velocity equal to 4.8 cm/s [208]. PET12_0.8 = particle diameter 100 nm; PET12_1.0 = particle diameter 70 nm; PET20_0.8 = particle diameter 20 nm. Reproduced with permission from MDPI.

Adsorption has been used as an effective method for air purification [209,210]. Activated carbon-based adsorption method has been conventionally used. Adsorption media based on advanced nanomaterials has been developed for IAQ management. Nanomaterials with high surface area and high storage capacity have been preferred for adsorption materials [115]. Swamy [211] designed an adsorbent nanomaterial for CO_2 adsorption. Using this nanomaterial, the CO_2 level was reduced to 50%. Moreover, nanofibrous materials modified with adsorbent nanomaterials have been proposed for VOC adsorption [212]. In this way, adsorbents were used for controlling safe IAQ by removing VOC and toxic gases. Buyukada-Kesici et al. [213] prepared polyamide 6 and cellulose nanocrystal-based nanocomposite as adsorbent. The nanomaterial was capable of treating VOC, especially toluene. Kadam et al. [214] designed electrospun adsorbent material based on polyacrylonitrile//β-cyclodextrin nanofibers for VOC and indoor pollutants. The polyacrylonitrile//β-cyclodextrin nanofibers had an adsorption efficiency of >95% for formaldehyde and ~66% for xylene. Moreover, nanocomposite had no toxic effects on human systems. Hence, polymeric nanocomposite-based adsorbents were efficiently used to remove indoor pollutants.

5.3. UV Photocatalysts

UV photocatalytic oxidation has been focused on purifying indoor air [215]. UV photocatalysts cause redox reactions of toxic gases and biological particles adsorbed on its surface for removal [216]. The metal oxide-based UV photocatalysts have been used [217]. The physicochemical properties of nanomaterials have been modified to attain high-performance UV photocatalysts. The nanomaterials have the capability for removing VOC, PM, COx, NOx, SOx, and other indoor environmental pollutants [218,219]. As a result, UV photocatalysts are proven promising for removing indoor pollutants and related diseases such as sick building syndrome [220]. Besides, UV photocatalysts have been used to prevent ozone depletion problem of the stratosphere. Arnawtee et al. [221] prepared lignin, carbon nanotube, and palladium nanoparticle-based UV photocatalyst through laser ablation. UV photocatalyst was used to remove VOC and dye traces from indoor air. Zan et al. [222] designed a polystyrene grafted TiO_2 nanocomposite for maintaining IAQ. Poly(vinylidene fluoride)/TiO_2 nanocomposites have been developed (using solvothermal method) as a UV photocatalyst for removing indoor VOC [223]. Moreover, Boaretti et al. [224] formed a UV photocatalytic system based on electrospun nanofibers of poly(vinylidene fluoride)/graphene/TiO_2 and poly(vinylidene fluoride)/graphene oxide/TiO_2 nanocomposites. The nanomaterial was used for removing or degrading indoor air pollutants such as VOC, acetaldehyde, and methanol. The photocatalytic activity of TiO_2, graphene/TiO_2, and graphene oxide/TiO_2 systems for removing acetaldehyde and methanol abatement was measured (Figure 13a,b). The resulting normalized data were analyzed (Figure 13c,d). In acetaldehyde degradation, the initial concentration was removed by using a catalyst in 15–20 min. On the other hand, neat TiO_2 took 40 min for complete degradation. According to the results of moles reacted per gram of catalyst, better performance of nanocomposite systems was achieved. Better dispersion of graphene, graphene oxide, and TiO_2 nanoparticles resulted in superior photocatalyst efficiency. In these UV photocatalysts, the inclusion of graphene and TiO_2 nanoparticles decreased band-gap energy facilitating electron mobility and photocatalytic activity [225].

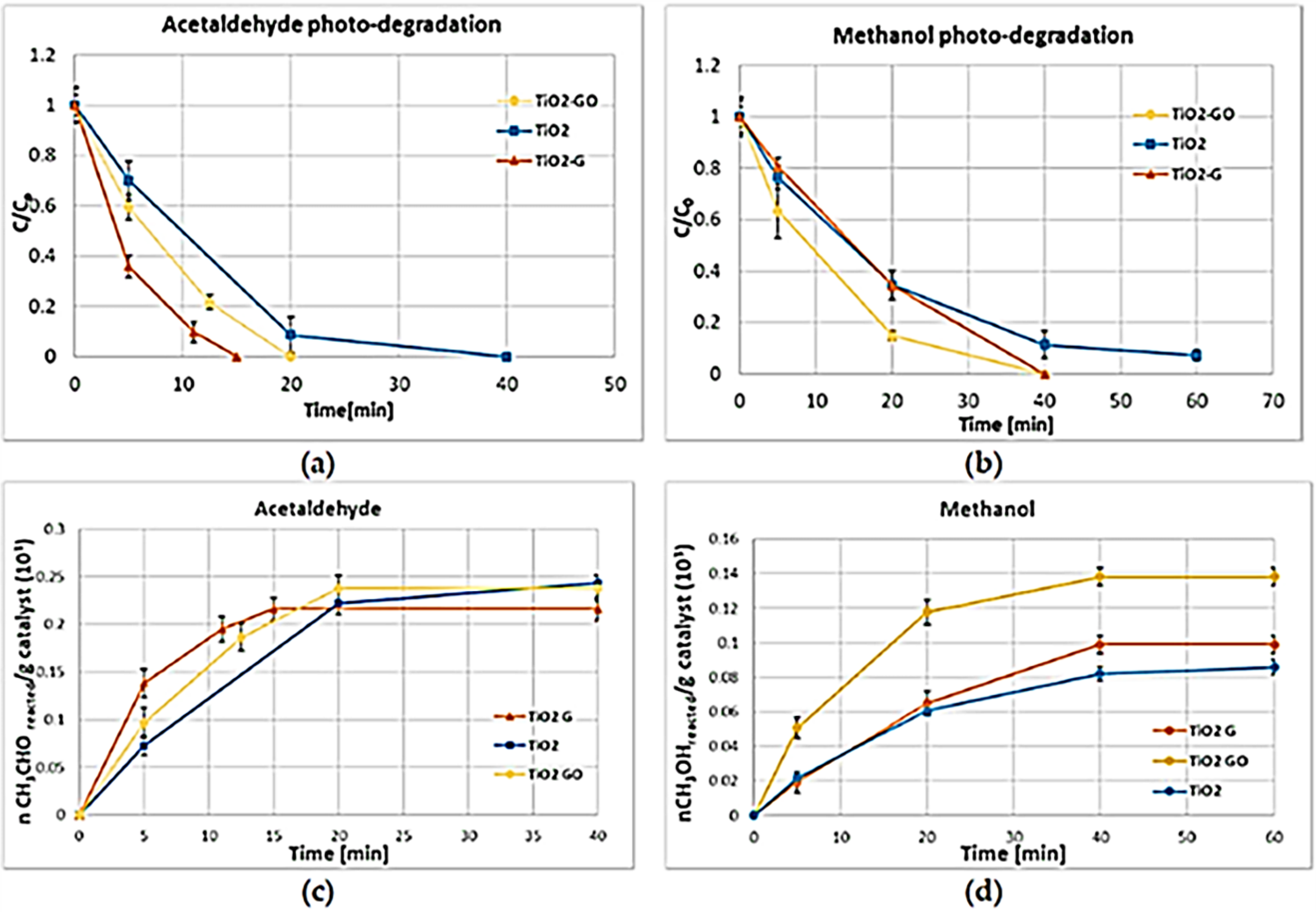

Figure 13. Acetaldehyde removal versus time (**a**) and normalized data on catalyst mass (**c**); Methanol removal versus time (**b**) and normalized data on catalyst mass (**d**) [224]. Reproduced with permission from MDPI.

6. Conclusions

As indoor air pollutants cause adverse human health effects, monitoring strategies/equipments have been developed for improving air quality by implementation in buildings and residences. An essential step to improve indoor air quality is the use of low-emission products and materials causing pollution. In this regard, combustion/burning utilizations and building heating equipment need to be optimized for limiting pollutant emissions. Construction materials such as insulating materials, paints, coatings, covers, furniture, etc. must be developed using safe and inert materials causing low VOC emissions. Building indoor car garages must be avoided to eliminate the chances of indoor CO pollution. Moreover, indoor surfaces need to be kept clean and dry avoiding any moisture for growing germs, bacteria, molds, etc. Keeping indoor pets can be avoided to minimize chances of indoor pollution. An important control and management step to maintain IAQ must involve indoor air circulation and ventilation systems. Although, ventilation can only avoid indoor air pollutants to some extent, PM, VOC, noxious gases, and microorganisms still remain in an indoor environment. Outdoor air is a rich source of indoor pollutants and cannot be avoided. Advanced IAQ technologies such as filtration, adoption, UV disinfection, UV photocatalyst, NTP methods, green vegetation, etc. must be adopted to minimize indoor pollution. However, indoor pollution cannot be completely avoided. For IAQ monitoring, it is important to develop advanced sensors for sensing hazardous indoor pollutants. Current technical developments demonstrate the effectiveness of using advanced nanomaterials in monitoring sensors, filters, adsorbents, and photocatalysts. However, precise working mechanisms and design necessities of these nanomaterials for innovative systems need to be thoroughly explored. Moreover, the development of nanomaterials-based air purification systems on large-scale faces design challenges related to material type and final IAQ system. In other words, several challenges need to be overcome for using new materials and products for removing indoor pollutants It is important to renovate existing buildings with equipment and devices supporting IAQ standards. It is important (i) to monitor IAQ on large scale; (ii) to properly educate people to avoid indoor pollution generation; and (iii) to take necessary action in case of indoor pollution. In the future safe IAQ level will be a performance indicator of our houses or buildings and society's foremost concern for health protection.

Briefly speaking, this review summarizes almost all possible indoor pollutants, their health effects, and required IAQ monitoring, control, and management technologies. The article presents the importance of using advanced nanomaterials in IAQ monitoring or management systems. The application of nanomaterials in IAQ systems opens future ways for a safe, healthy, and ecological indoor environment.

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