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Review on scientific studies and commercial indoor air purification devices: Focus on plasma-catalytic technology

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ABSTRACT

According to World Health Organization, urban populations spend 90 % of their time in indoor environments. Accentuated by the recent COVID-19 pandemic, this raises important concerns about the quality of the indoor air, which often contains various types of contaminants within three main categories: biological, volatile organic compounds, and particulate matter. Several technologies already exist for removing contaminants from indoor air, such as electrostatic based methods or filtration. Although these technologies are well established, they often target only one or two groups of contaminants. This review focuses on a promising technology: nonthermal plasma combined with catalysts. After an overview of indoor air contaminants, their sources, and the typical methods used for their removal, a highlight is put on the available commercial indoor air purification devices. The latter are rarely described in literature, and the comparison with lab-scale experiments are difficult due to the lack of information and available data from the manufacturers. The limitations of those systems are also discussed. As most of these commercial devices use combinations of various conventional technologies, the last part focuses on the ongoing research on plasma-catalytic systems. The main mechanisms are presented along with recent literature. Finally, some perspectives for its future development are proposed.

List of abbreviations

IAQ	*Indoor air quality*
IAP	*Indoor air purification*
VOCs	*Volatile organic compounds*
PM	*Particulate matter*
ESP	*Electrostatic precipitator*
HEPA	*High-efficiency particulate air*
PCO	*Photocatalytic oxidation*
NTP	*Nonthermal plasma*
RH	*Relative humidity*
CADR	*Clean air delivery rate*
IPC	*In-plasma catalyst*
PPC	*Post-plasma catalyst*
DBD	*Dielectric barrier discharge*
UV	*Ultraviolet*

1. Introduction

1.1. Indoor air quality (IAQ)

Research on the urban population has shown that people spend more than 90 % of their daily lifespan in indoor environments [1]. In addition to indoor home environments, people spend a significant percentage of their time within office spaces, educational institutions, vehicles, and various industrial and commercial environments. According to a study conducted in North America, adults spend approximately 87 % of their time within indoor environments, while the remaining portion of their time is spent inside vehicles (6 %), but only about 7 % in outdoor activities [2].

Indoor air often contains pollutants concentrations that are 2–5 times higher than those typically found in outdoor air. A pollutant released indoors is approximately 1000 times more likely to be inhaled than the same amount released outdoors [3]. In this modern era, high performance homes are typically constructed to be more airtight, resulting in significantly reduced fresh air exchange compared to older, less efficient

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homes.

Due to these facts, exposure to indoor air pollution substantially influences human health and well-being, as well as their productivity in the workplace [4]. Nevertheless, most of the research on air quality control is concentrated on outdoor environments, while indoor air quality and its effects have not been largely studied. Recently, there has been a growing emphasis among scientists and the public on the hazards linked to IAQ due to the research findings that confirmed a higher level of contamination in indoor air compared to outdoor air [5,6]. Indoor air contains a wide range of dangerous components that can lead to respiratory, cardiovascular, and oncological diseases [7,8]. The nature and complex compositions of indoor air pollutants substantially vary due to persistent changes in living styles and the materials used in indoor environments. Recent COVID-19 caused by airborne SARS-CoV-2 corona virus with all its global socio-economic consequences underlined the severity of the IAQ and urgency for a comprehensive investigation into this issue, as well as development of indoor air purification (IAP) technologies.

Over the past 50 years, people's lifestyles have significantly changed, especially in industrialized countries. Since sick building syndrome, multiple chemical sensitivity, and building-related illness have all been linked to poor IAQ, this topic has gained significant attention [9,10]. Additionally, according to World Health Organization (WHO) research, indoor air pollution was a factor in 4.3 million of the seven million premature deaths that occurred in 2012 because of air pollution [11]. Contaminated indoor air plays a significant role in the transmission of nosocomial infections in hospital settings [12,13]. It has been demonstrated that any improvement in IAQ will positively impact productivity, health, and the economy. The U.S. Environmental Protection Agency (EPA) has identified poor IAQ as a significant issue that has a direct impact on the health of children. WHO identified IAQ as one of its public health concerns in 1979 and issued precise IAQ standards in 2010.

1.2. Indoor air pollutants and their sources

In general, indoor air pollutants refer to several chemical, biological, and physical agents that could impact human health or cause discomfort [14]. They can generally be divided into the following categories:

Biological Pollution: The indoor air environment comprises a wide variety of biological pollutants, including bacteria, fungi, viruses, molds, and their spores, endotoxins, mycotoxins, and other byproducts. Animals, plants, construction materials, concealed food spills, and stagnant water are typical sources of biological pollutants [15]. Chirca reported that bio-contaminants are widespread in indoor air, including in highly regulated environments such as modern hospital operating rooms [16]. Pathogenic bacteria and their spores can last in a hospital environment for variable durations, ranging from hours to months. The duration depends on various aspects such as the specific location, quantity, humidity, formation of biofilms, inherent resistance of the organisms to different cleaning agents, and the prevailing local conditions [17].

Bio-aerosols refer to airborne suspended particles in air that are either produced by living organisms or discharged by them. Bio-aerosols typically have a diameter ranging from 0.1 to 100 μm [18]. However, smaller bio-aerosols exhibit a prolonged presence in the atmosphere, while bigger ones tend to accumulate on various surfaces. Transmission of pathogens through air bio-aerosols is a critical pathway for the spread of airborne diseases, as airborne pathogenic microorganisms cause multiple harmful infections [19].

Chemical Pollution: Indoor air is contaminated with a broad range of chemical substances. Hospital indoor environments mostly contain disinfectants, including ethylene oxide, primarily employed for sterilization purposes [20]. Office environments equipped with photocopiers, computers, and other electronic devices emit several pollutants, including ozone (O_3), acetone, ethylbenzene, toluene, and benzo-pyrene [21]. Tobacco smoke, improperly vented gas or oil-burning appliances, and smoke from wood-burning and fireplaces generate formaldehyde, which is considered one of the major chemical pollutants in enclosed environments. Formaldehyde in low concentration is also often released from paints, flooring, and furniture. Gallego et al. [22] identified 130 distinct volatile organic compounds (VOCs) in private residences, with alkanes being the most prevalent type (32 %), followed by aromatic hydrocarbons (17 %).

Particulate Matter Pollution: A wide variety of solid or even liquid particles that are small enough to be airborne and inhaled by humans are called particulate matter (PM). The size of the particles varies greatly, but the smaller ones are the most dangerous to our health because they can get into our lung alveoli and can be then transported into the blood stream [23]. Indoor air frequently contains ultrafine particles with diameters up to 100 nm. However, indoor detection rates for PM_{10} particles (particulate matter with aerodynamic diameter <10 μm) and $PM_{2.5}$ (<2.5 μm) are higher. Ultrafine particles $PM_{0.1}$ (<0.1 μm) are typically not measured, although the recent WHO global air quality guidelines require to expand the existing air quality monitoring by integrating ultrafine particles [24].

Physical factors influencing indoor air pollution: The assessment of indoor pollutants is significantly influenced by air temperature and relative humidity (RH), which also impacts the sensation of comfort. High temperatures and humidity promote biological pollution by supporting the growth and spread of bacteria and molds. These environmental conditions influence chemical interactions among the substances present in indoor air. Lowering temperature at high RH conditions leads to condensation which promotes formation of aerosols that may contain microbiological pollutants.

Most human exposure to air pollutants occurs indoors, from various sources, including outgassing from furnishings, floors, wall coverings, paints, glues, waxes, polishes, cleaning supplies, personal care items, tobacco smoke, heating devices, cooking activities, etc. In addition to other variables like door and window openings, air exchange rates, housing age and size, and building upgrades, external pollutant levels can also have an impact on the concentration of air pollutants inside a building [25]. Stoves, boilers, smokers, and cookers that use gas are significant emitters of indoor nitrogen oxides (i.e. NO, NO_2), and $PM_{2.5}$. Mites, bacteria, mold, fungi, spores, endotoxins, mycotoxins, and other types of living organisms with extremely variable and complicated features make up most biological pollutants [26]. Table 1 provides information about indoor air contaminants and their various associated health impacts.

2. Conventional indoor air purification (IAP) methods

Conventional methods for IAP from chemical (gaseous pollutants, particulate matter) and biological contaminants are based on various physical and chemical techniques. The use of a given method for the removal of any contaminant depends on several factors such as:

- The nature of the contaminant and its concentration
- The gas flow rate and the requirements for the purity of clean air
- The relative humidity and temperature
- In the case of PM removal, it depends mostly on its size and resistivity.

The methods can be divided into those that capture pollutants without their actual removal (**non-destructive methods**) and those that remove pollutants and convert them into harmless substances (**destructive methods**). Fig. 1 shows the main methods used for IAP and pollutants they can effectively remove. A brief overview of each of these methods is given below.

2.1. Non-destructive methods

2.1.1. Electrostatic precipitation

Electrostatic precipitation (ESP) is a physical process in which PM in

Table 1
Indoor air contaminants and their associated health impacts.

Contaminants	Sources	Health Impact	Ref.
Biological Contaminants			
Allergens	Furry pets, dust mites	Asthma	[27]
Bacteria, mold, fungi, and spores	Sneezing, hidden food spills, standing water and outdoor environments	Chronic disease, respiratory and allergic symptoms	[28]
Endotoxins and Mycotoxins	Presence of cats and dogs, lower ventilation rate, increased amount of settled dust	Asthma, reduced lung function	[29]
Chemical Contaminants			
Smoke	Tobacco smoke	Lung cancer, respiratory illness, premature mortality, and coronary artery disease	[30]
Coal and biomass fuels combustion product	Cooking and heating	Combustion of fuels releases CO, particulates, N_2O which increases the risk of lung cancer and asthma	[31]
Carbon monoxide (CO)	Gas stoves, furnaces, fireplaces and cigarettes, wood stoves, vehicle exhaust from attached garages	Headache, nausea, fatigue	[32]
Formaldehyde (HCHO)	Tobacco smoke, improperly vented gas or oil burning appliances, smoke from fireplaces and wood-burning, paints	Eye, nose, throat irritation, asthma, and possible carcinogen	[1]
Volatile organic compounds (VOCs)	Room deodorizers, carpets, paints, cigarette smoke, and recently dry-cleaned clothes	Headaches and loss of coordination, eye, nose, and throat irritation, damage to the liver, kidneys, or central nervous system	[33]
Ozone (O_3)	Air ionic purifiers, printers and copiers, electrostatic filters	Eye irritation, headaches, dizziness, chest tightness, and visual disturbances	[34]
Particulate Matter			
Ultra-fine particles ($PM_{0.1}$)	Cooking, outdoor air, combustion activities	Serious impact on heart and lungs	[35]

the gas stream are electrically charged and then separated from the gas stream by the effect of the electric field [36]. Efficiency of these devices reaches up to 99 %. When compared to other methods, ESP is also suitable for ultrafine particles $PM_{0.1}$ (particles smaller than 0.1 μm). The pressure drop is usually small (less than 1 kPa), allowing ESP to be used at high flow rates. The charging of PM is usually achieved by corona discharge. A high voltage is applied to a pin or a wire, generating a strong electric field which ionizes the gas around. PM charging is achieved either by electric field due to ion capture (effective for bigger PM), or by thermal diffusion due to random collisions of ions (effective for $PM_{0.1}$). The charging of particles is very fast and depends on the ion density, the effective cross-section of PM, and electric field intensity. For $PM_{0.1}$, it is however very slow, and the thermal diffusion charging prevails.

Resistivity of PM is an important parameter for effective PM capture. It is a measure of the PM's ability to carry an electric charge. It depends on the chemical composition of the gas, the nature of PM and the gas temperature [37–39]. PMs with low resistivity have better ability to carry an electric charge. Those can be easily charged but also lost after their capture on the electrode, due to their neutralization or opposite polarity charging, and finally repelled back into gas. Repeated entry of already captured PM back into the gas stream decreases the efficiency of the ESP device. The effect is pronounced for small PM but can be eliminated by dosing liquid adhesives, such as oil or water. On the other hand, if the resistivity of PM is too big, the particle is difficult to charge and to remove. The deposited layer of collected PMs on the collection plates holds a charge, which creates a strong local electric field, weakening the electric field given by the electrode geometry [40]. In an extreme case it can lead to a change of the gap polarity and induce a so-called back corona discharge, or to the sparking of the system. ESP devices are categorized with respect to the shape of electrodes (cylindrical or planar), arrangement of charging and collection sections (one-stage and two-stage), presence of water (dry, wet, semi-wet) and polarity (positive and negative). The negative one is most often used for large industrial applications (e.g. coal boilers) for a large range of stability and higher working voltages, while positive ones are mainly used for small indoor devices, since they produce less O_3. In general, ESPs are very effectively capturing PM in a wide range of sizes, have low energy consumption, low pressure drop, and easy maintenance (few moving parts) [41]. However, they are not useable in the presence of explosive or flammable substances, as well as sticky PM often present in industrial exhausts. Their costs are usually high due to high voltage equipment. But generally, these issues, costs apart, are not relevant for smaller scale IAP, and hence makes them a very efficient and widespread method for IAP.

2.1.2. *Mechanical filtration*

Mechanical filters (also bag or textile filter) are mechanical devices using precipitation, capture, and diffusion to collect PM up to a specific size on the surface of filter bags.

High-efficiency particulate air (HEPA) filters: One of the most common and effective methods for air purification is the so-called HEPA filtration. HEPA filters are made of fine mesh of fibers that can capture particles as small as 0.3 μm with a 99.97 % efficiency [42]. This includes both PM and biological contaminants. Filters can be made of various materials including cotton, wool, nylon, polymer fibers, Teflon, etc., and are usually stretched on frames. The key properties of the used HEPA media are temperature, chemical and mechanical resistance, binding, weight and strength. The main advantage of fabric filters is their very high efficiency due to the dense arrangement of the fibers. However, HEPA filters have their own set of challenges, such as the need of their regular replacement to maintain their effectiveness. Also, their dense nature can restrict the airflow, which becomes the reason for a considerable pressure drop in indoor environments. Lastly, HEPA filters are designed to capture particles but do not remove odors, gases, or VOCs. The performance of a mechanical filter depends on various factors, such as the type of filter, air flow rate and velocity across the filter, the material used for the filter media, and other associated processes [43].

Electret filters (and electrostatic filters): electrets are a type of dielectric material holding sufficient charges within their volume to spontaneously generate an electric field. They can be made of dielectric fibers, usually quartz or other forms of SiO_2, or from polymers (especially fluoropolymers). These, in addition to their mechanical efficiency, can attract uncharged PM by the dielectrophoretic force, as well as charged PM by the Coulomb force. Electret filters display a wide range of efficiency against PM, going from $PM_{0.1}$ to PM_{10} [44], but are also used for aerosols or bacteria removal [45]. Of note, electrostatic filters differ from electret only by the fact that they need an external source to generate the electric field, but the principle and efficiency for removal of the pollutants is the same.

2.1.3. *Adsorption*

Air purification based on adsorption utilizes adsorbent materials to remove various airborne pollutants, gases and odors from the indoor environment. Unlike filtration methods that physically trap particles, the adsorption air purification method uses specialized adsorption materials, such as activated carbon, silica gel, zeolites, and some polymers, to trap and remove gases, odors and VOCs from the air. The process is based on the principle that the adsorbent materials have a large surface area and high adsorption capacity (especially activated carbon) with

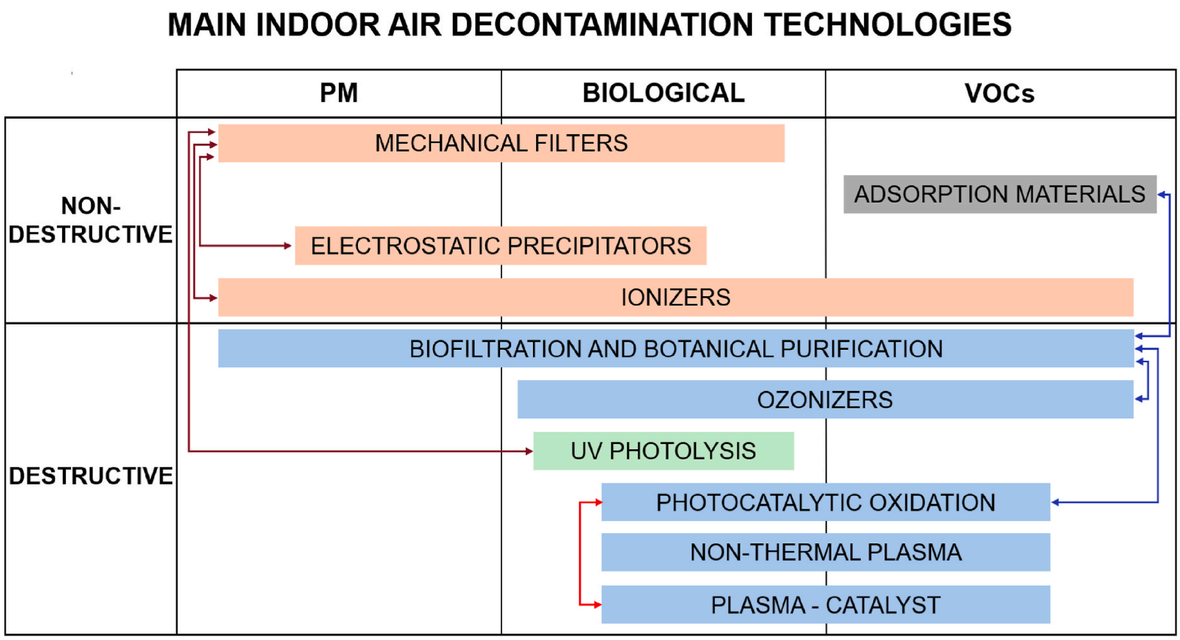

Fig. 1. Main purification technologies for indoor air and the target pollutants against which they are efficient.

numerous pores and channels that can capture a large volume of gases and VOCs [46]. However, high RH and pollutant load variations compromise the adsorbent efficiency. Additionally, adsorbents should be regularly replaced to avoid the re-emission of the already adsorbed compounds. Another negative feature is that airborne bacteria can accumulate on the surface of the adsorbent and thrive due to the strong biocompatibility of carbon materials [47].

2.1.4. Ionization

Ionizers are devices employing high voltage to ionize the surrounding air and produce ions. They are especially efficient for airborne particles removal [48,49] (PM, tobacco smoke, bacteria), but also against VOCs [50]. The main mechanism of such devices is the generation of N_2^+ and O_2^- ions. Those ions immediately form clusters with molecules present in air such as H_2O, in turn "sticking" to the airborne particles and allowing their removal, either with subsequent filtration or due to natural deposition on the surfaces. Those systems must be regularly cleaned up, similarly to the collection plates in ESPs. Although ionizers can make the air feel fresh, they do not completely remove the particles. Besides, ionizers also produce small amounts of O_3, usually from ten to hundreds of parts per billion (ppb) [48,49]. This is an unwanted byproduct as it is toxic, and it was found to have little potential for pollutants removal when produced at concentrations lower than public health standards. This technology is one of the most used for indoor air cleaning, along with HEPA filters, in available commercial devices for IAP, as it will be described in section 3.

Other non-destructive methods exist, both for IAP, as well as more general air treatment that could be adapted to indoor air. But the common limitation is the fact that they only shift the pollutants somewhere else or create secondary pollution, rather than destroying them. The section below presents the available destructive methods used for IAP.

2.2. Destructive methods

2.2.1. Biofiltration

Biofiltration of gases is done by passing pollutants through a porous bed (soil, sand, pellets) in which micro-organisms are fixed. Microorganisms reduce various contaminants including odors and VOCs, but also bacteria [51], as they consume them and use them as an energy source [52,53]. Usual types of microorganisms are fungi, bacteria and actinobacteria. The biofiltration requires strongly aerobic environments, optimum moisture and temperature for activity and reproduction, gas cooling, eventually a gas pre-treatment in form of humidification, PM removal, or eventual heating/cooling. Several drawbacks of such a technique should be mentioned, especially the low treatment capacity (i.e., flow rate), the concentrations of pollutants that can effectively be removed, and the necessity to replace microorganisms. However, even if this method is not the first choice for typical indoor environments (school, houses, etc.), it becomes highly relevant for space applications such as space stations and future space missions.

2.2.2. Botanical purification

It is a method employing phytoremediation to purify air. It uses the plants, depending on their metabolic activities, to remove the pollutants from the air. Such pollutants, especially VOCs but also PM, can be absorbed, catabolized and degraded by the plants [54]. Additionally, to these purification properties, utilizing plants as an IAP also brings several other benefits, such as its low cost, it is environmentally friendly, low maintenance, and have positive effects on health and task performance, reduce the level of stress and improve comfort [55]. However, in the same way as biofiltration, it is mostly effective for low concentrations and flow rates. The types of plant to be chosen might depend on the pollutants to be removed, and it can also depend on the day and night cycles [56].

2.2.3. Ozonation

Ozonizers are devices generating ozone (O_3). Several technologies can be employed for this purpose, such as corona discharges, dielectric barrier discharges, or vacuum UV radiation (185 nm). The aim is to dissociate the O_2 molecules present in air to O atoms, which can recombine with other O_2 molecules to form O_3. Due to its high oxidation potential, O_3 can be used for oxidation of pollutants, especially VOCs [57], and for bio-decontamination [58]. Commercial ozonizers are cylindrical dielectric tubes equipped with inner and outer cooled electrodes, with small discharge gaps (0.5–1 mm) driven by AC high voltage (HV) of 0.5–5 kHz in air or oxygen. For small lab-scale devices, ozonizers usually consume power up to 5 W, have typical O_3 production capacity around 0.5 kg/h and specific energy consumption of 10–20 kWh/g O_3. Ozonation is used for gas and odor purification, but mainly for water treatment including sterilization of drinking water, in breweries and winemaking industries, industrial wastewaters treatment and food processing. Since the O_3 generated is generally in excess compared to its quantity necessary for decontamination, the residual O_3 must be destroyed before the cleaned air stream exits from the device. This is usually achieved by thermal or catalytic destruction using various metals or metal oxides catalysts (Ni, Pd, Mn). Another possibility is adsorption and reaction with activated carbon that leads to CO_2 formation, while carbon is gradually degraded and must be eventually replaced. Generally, as O_3 is also one pollutant targeted to be removed from indoor air, and since the technology is also quite old, this method is not dominant anymore for IAP.

2.2.4. Ultraviolet (UV) photolysis

UV radiation can significantly reduce indoor air pollutants by neutralizing harmful microorganisms such as bacteria and viruses. The UV lamps are commonly installed in heating, ventilation, and air conditioning (HVAC) systems to treat air as it circulates, preventing contaminants from reaching indoor living spaces. The elimination of bioaerosols has been found to be influenced by UV radiation. UV photolysis air purification methods primarily rely on the germicidal properties of UV radiation, typically within the wavelength range of 200–280 nm, to disinfect various bacteria and viruses and purify the air [59]. UV photolysis can effectively destroy the DNA and RNA of bacteria, viruses, and mold species, rendering them inactive and unable to reproduce [60,61]. The efficiency of this process relies on several factors, including the molar absorptivity of the targeted gas-phase pollutant at the specific wavelength, the intensity of the UV source, and the initial concentration of the contaminants.

However, the application of UV photolysis is limited due to several associated challenges. UV-C radiation has limited penetration and can be blocked by objects and surfaces, creating “shadow regions” where microorganisms may not be effectively disinfected. In addition, UV-C radiation is harmful to the eyes and skin and can cause damage upon direct exposure [62]. UV-C lamps degrade and reduce their radiance over time. Furthermore, some UV photolysis air purifiers may produce O_3 as a byproduct during operation, which must be then decomposed by other methods.

2.2.5. Photocatalytic oxidation (PCO)

UV photocatalytic air treatment is an advanced air purification technique that integrates UV radiation and photocatalysis to oxidize and degrade airborne contaminants, VOCs, bacteria, viruses, and mold species [63]. In this process, a semiconductor material serves as a catalyst and becomes activated upon exposure to UV radiation. When the wavelength of UV radiation exceeds the band gap energy of the photocatalyst, it initiates oxidation and reduction reactions. Positively charged holes and negatively charged electrons interact with water and oxygen molecules, generating reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide ions ($O_2^{\cdot-}$). These ROS then degrade and neutralize both biological and chemical contaminants. Fig. 2 illustrates the photocatalytic mechanism involved in the treatment of biological and chemical pollutants under UV irradiation.

Various research groups have demonstrated the advantages of PCO for the decomposition of chemical contaminants such as nitrogen oxides (NOx) and VOCs [64]. Photocatalysis has also shown antibacterial effects in addition to its ability to mineralize various organic compound [65]. Currently, TiO_2 is the predominant photocatalyst in use. It is cost-effective, non-toxic, compatible with living organisms, and exhibits excellent photo-efficiency and activity [66]. A study conducted by Vildozo et al. [67] investigated the application of TiO_2 in PCO to treat mixtures containing 2-propanol and toluene. The concentrations used in the study, ranging from 80 to 400 ppb, were representative of indoor air pollution. Under low humidity conditions, the conversion efficiency of both pollutants approached 100 %, however, the conversion efficiency of toluene dropped to 50 % when tested under a RH of 60 %. Daikoku et al. [68] examined the effectiveness of photocatalysis in inactivating influenza aerosols. They reported that, within 5 min of treatment using a photocatalytic air cleaner, more than 10,000 plaques forming units of the influenza virus were eliminated.

Despite extensive research, several challenges remain to be addressed, including the effects of RH, the selection of catalyst/catalyst characteristics (e.g., shape, size etc.), and the generation of gaseous byproducts [69,70].

2.2.6. Nonthermal (cold) plasma (NTP)

Plasma is a gaseous state of matter characterized by a high degree of ionization, resulting from the application of high-voltage electrical discharges. It typically consists of electrons, positively charged ions, and neutral particles, including atoms and molecules. The high energy electrons and charged ions further react with surrounding molecules, leading to the formation of free radicals and oxidizing species. This process facilitates the inactivation of bacteria and viruses, the disruption of chemical bonds, and the conversion of chemical pollutants like VOCs into CO_2 and H_2O [71–76]. Compared to thermal plasma and catalytic thermal oxidation, cold plasma or NTPs offers significantly lower energy

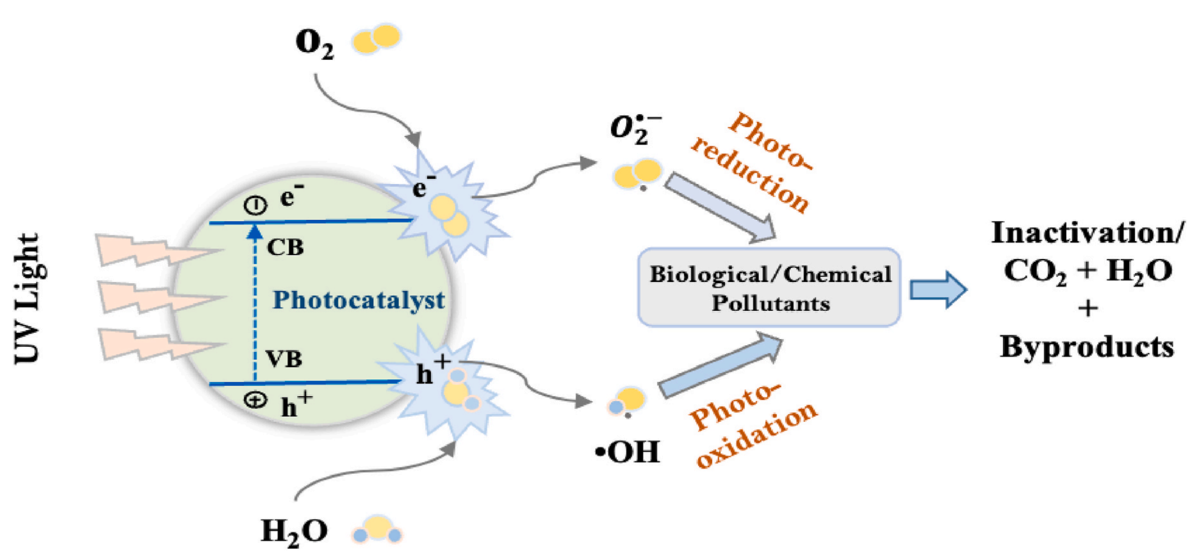

Fig. 2. Photocatalytic mechanism action in biological/chemical pollutants treatment under UV irradiation.

consumption while maintaining high efficiency in the removal of a wide range of chemical and biological contaminants.

The transmission of bacteria and viruses over long distances through indoor air might lead to adverse health effects. Currently, there is limited knowledge regarding the transmission of airborne diseases, the underlying mechanisms that regulate them, and the development of preventive strategies to mitigate their impact. Airborne transmission poses significant challenges, and while a few relief methods are available, they are insufficient. The transmission of disease from airborne microorganisms can be attributed to two key factors: aerosol transport and aerosol infectivity. UV radiation (photolysis) alone will only be able to address aerosol infectivity, and particle filtration only addresses the transport of aerosol. Unlike filtration and UV radiation, NTPs can address both aerosol transport and aerosol infectivity by charge-driven filtration and by reaction with different reactive plasma species, respectively. As a result, NTP reactors are increasingly being explored for their potential to inactivate and eliminate aerosolized microorganisms from enclosed environments [77]. The most used configuration for IAPs include, surface DBD reactors [71], packed bed reactors [72], corona discharge reactors [78], and excimer UV reactors [79].

NTPs have emerged as an advanced and effective technique for disinfection and sterilization across several industries and public health sector, owing to their unique characteristics and operational mechanisms. NTP processes operate at or near room temperature, making them particularly suitable for preserving the structural integrity of heat-sensitive materials such as plastics, electronics, and medical equipment [80]. The sterilization process using NTP involves the generation of a wide range of reactive species, including reactive oxygen and nitrogen species (RONS), in addition to UV radiation and electric fields [81]. This reactive species plays a crucial role in destroying microorganisms' DNA, proteins, and cell membranes, leading to their inactivation and ensuring high sterilization efficiency [82]. A key advantage of NTP technology lies in its ability to effectively eliminate a wide range of microorganisms, encompassing bacteria, viruses, and fungi. This versatility makes NTP a valuable tool in diverse sterilization contexts, such as healthcare settings for indoor air sterilization and the treatment of low concentration chemical and biological pollutants of indoor air.

Furthermore, the NTP approach is a dry sterilization method, obviating the need for chemical agents or water. This feature is particularly advantageous in scenarios where moisture control is critical to prevent material degradation or contaminants. The cost-effectiveness of NTP is further enhanced by its dry nature, which reduces resource consumption and minimizes waste generated by traditional wet sterilization methods [83]. Additionally, NTP supports environmental sustainability by reducing reliance on chemical disinfectants and limiting potential adverse environmental impacts. Industries can potentially mitigate their environmental footprint and advance sustainable and environmentally friendly operations through the utilization of NTP for sterilization purposes.

Unlike controlled environments such as laboratories, IAP is significantly influenced by environmental factors, especially RH [84,85]. RH plays a vital role in characterizing plasma, as it is an environmental parameter that fluctuates continuously. RH influences multiple parameters like electrical parameters, i.e. discharge current and power, the generation of different reactive species (N, N_2*, OH, O_3, etc.), and the disinfection/decomposition efficiency of NTPs [86]. In this context, Ki et al. [84] investigated the impact of RH on the discharge plasma in a chamber measuring 0.175 m^3. Their findings revealed that under high RH conditions, the concentration of •OH and H_2O_2 increased twofold compared to low RH conditions. In contrast, the concentration of O_3 was reduced to half.

However, even if NTP proved to be an efficient method, it can still produce high amounts of byproducts that are sometimes more toxic than the initial pollutants. Therefore, researchers are exploring combinations of plasma with other technologies to minimize toxic byproducts formation and increase overall efficiency. In this context, Islamov and Krishtafovich [87] employed a silver-based wire electrode to suppress O_3 generation. They observed that the rate of O_3 production decreased with increasing wire temperature. Specifically, at a temperature of ~46 °C, O_3 generation was reduced by 53 % using an Ag:Mn = 0.85:0.15 wire electrode. Similar findings have been reported by other research groups, indicating that both the material of the corona wire and the application of heat can effectively suppress O_3 formation [88,89]. For instance, Kim et al. [90] used a carbon fiber ionizer and reported that the maximum O_3 concentration in a 30.4 m^3 test chamber over 12 h of continuous operation was only 5.4 ppb, which is significantly lower than the current indoor air quality regulation limit of 50 ppb.

2.2.7. *Plasma-catalysis*

To overcome the limitations of individual air purification methods, several combined approaches are currently under investigation for IAP, as illustrated in Fig. 2. Among these, the integration of NTPs with heterogeneous catalysts, referred to as plasma-catalysis, is a key focus of this review. In the plasma-catalysis, a potential synergistic interaction between plasma and the catalyst may enhance both the removal efficiency and the total oxidation of the pollutants.

The presence of a catalyst increases the likelihood of surface reactions between the reactants and reactive species, resulting in more selective pathways and improved pollutant degradation efficiency. Consequently, the textural properties of the catalyst, such as specific surface area, pore volume and size, particle size, and crystal phase, play a critical role in determining plasma-catalyst performance. The detailed mechanisms and applications of this combined strategy are discussed in section 4.

2.2.8. *Ozone-catalysis*

In DBD-NTP reactors, O_3 often emerges as a dominant primary species. In these reactors, a considerable amount of O_3 remains even after pollutant degradation, functioning as a byproduct. This residual O_3 can play a significant role in a post-plasma catalytic reactor. First, it serves as a powerful oxidant, enhancing the breakdown of pollutants beyond the plasma zone. In this context, researchers have developed plasma–catalyst hybrid systems, incorporating catalysts like TiO_2, MnO_2, CuO, or Ag-based zeolites after the DBD reactor to utilize the remaining O_3 for enhanced oxidation of pollutants [91,92]. For instance, Wang et al. [93] showed that MnO_x–CeO_2 catalysts placed downstream of the plasma reactor improved toluene removal efficiency, primarily due to the O_3-driven secondary oxidation. On the other hand, if left untreated, O_3 can pose health and environmental risks. Ye et al. [91] found that $MnO_x/\gamma\text{-}Al_2O_3$ catalysts placed after the plasma reactor could effectively convert residual O_3 into reactive oxygen species, simultaneously boosting toluene degradation. Hence, catalysts can also serve to decompose excess O_3, converting it to oxygen before exhaust. This dual role of catalysts – pollutant oxidation and O_3 suppression – makes post-plasma catalysis an essential design strategy in NTP systems.

2.2.9. *Other combination technologies*

Apart from plasma-catalysis, researchers are also developing various indoor air treatment technologies by combining two or more methods into a single or multi-stage system. It is well understood that specific technologies are effective against certain types of pollutants. For example, ionizers are primarily effective against biological pollutants, while HEPA filters are mainly used for trapping particulate contaminants. Therefore, there is a need to develop comprehensive technology capable of addressing all types of pollutants, regardless of their initial concentration or nature.

In this context, there are a few studies that have experimented with different combinations, such as HEPA filters + ionizers, PCO + particle precipitators, and NTP + HEPA + ESP. For instance, Krugly et al. [94] developed a gas-to-particle conversion process to eliminate VOCs from ventilation air. This technology integrates plasmolysis, photolysis, particle precipitation, particle growth, and catalysis. They tested the system in a laboratory setting using simulated polluted air containing various VOCs. The overall VOC removal efficiency ranged from 75.7 % to 99.8 %. Residual particles and O_3 were removed or decomposed by up to 99.99 % using a needle-to-plate type ESP and an ozone-absorbing catalyst. Li et al. [95] developed a prototype system that incorporated conventional UV-C radiation into a PM filtration system to mitigate airborne bacteria and PM in indoor environments. This prototype achieved complete (100 %) inactivation of viable airborne bacteria and removed up to 91 % of PM_{10} and 87 % of $PM_{2.5}$. Similarly, Srivastava et al. [96] used a UV-C and filtration system in an indoor environment to clean the air carrying COVID-19 virus. They observed that using 100 % outdoor air significantly reduces the infection risk, but it also increases energy costs. They showed that the infection risk decreased from 27 % to 3.1 % as the proportion of outdoor air increased from 10 % to 100 %, respectively.

Lu et al. [97] combined a 222 nm KrCl* excimer lamp with air ionizers to inactivate aerosolized bacteria and viruses. They observed a significant improvement in inactivation efficiency when using the combined system compared to individual tests. The combined system enhanced the inactivation efficiency by 116 % for aerosolized pathogens, demonstrating a clear synergistic effect. Ratliff et al. [98] designed a system using bipolar ionization and photocatalytic devices to check its effectiveness on large scale microorganisms in the air and the surfaces in an operational scale test chamber with a recirculating HVAC system. The bipolar ionization and photocatalytic devices inactivate 0.88 log and 1.8 log reduction, respectively, in 60 min of treatment time. Note that an n-log reduction corresponds to a concentration of remaining contaminant of 10^{-n} times the original concentration. But none of the technologies are effective on MS2 bacteriophage on surfaces in the test chamber.

There is extensive research on combining various methods for indoor air treatment, primarily involving ESP, ionizers, HEPA filters and UV-C. Although plasma-catalysis has been widely studied for the treatment of VOCs in flow reactors, there is a lack of research on integrating NTP processes with catalysis for the purification of indoor environments.

3. Existing commercial IAP technologies

This section intends to give an overview of some of the existing commercial systems that have been developed. With the growing awareness of the potential problems and health issues related to indoor air contamination, air cleaners (air purifiers) have been developed by different companies. Often portable, such devices can easily be installed in hospitals, schools, offices or even in homes and aim at providing a clean and pollution-free environment to individuals. Reports evaluated the air purifiers market size to be worth 16 billion USD in 2023 and is estimated to double by 2030 [99]. While mechanical filters still hold the strongest parts of the market (~50 %), electrostatic based systems have been expanding and captured the interest of several big companies, as well as startups. In most cases, those IAP systems are not relying on only one of the technologies mentioned in the previous section but rather combine them to reach higher removal efficiency and target more pollutants.

While most of the research papers and reviews of IAP focus on the ongoing research, the development of new solutions, and the underlying mechanisms governing the pollutants removal, not much focus is put on the commercial technologies already available. As the scope of the journal is electrostatics, the commercial systems discussed here have been limited to those containing at least one electrostatic element (e.g., ionizer, electrostatic precipitator, electrical discharge of any type). Additionally, only companies and products where sufficient information and data are available have been selected. We also selected mainly companies that have a long history in the market of air cleaning/conditioning devices and employ mostly proven technologies in their devices. Such information includes the technology used for IAP, the type of pollutants targeted, the removal efficiency, and reports concerning the measurements for the latter.

3.1. Details of technologies used in IAP devices

Table 2 presents a list of companies selling IAP systems. Note that the list is not exhaustive, and that the information discussed herein are "as provided by the manufacturer". The first five are well-known international groups (*Sharp, LG, Mitsubishi, Toshiba, Daikin*), while the last five are smaller specialized companies (*PlasmaAir, PlasmaCleanAir, BlueAir, AirOasis, Oxytec*). Generally, the products from the bigger companies are the ones where the most information is available concerning the technology and the test measurements for the efficiency. Focusing first on the technology used, the largest part of them use a combination of different decontamination methods. Almost all of them use pre-filters (mechanical filters) to trap particles with sizes or 10 μm or bigger, an electrostatic element, and other mechanical filters. A UV radiation unit is also added for almost half of the products found.

For the electrostatic element, ionizers are the most widespread. Depending on the company, even if the name is the same, the technology employed can be different, and hence the role of this element on the decontamination of the pollutant might differ. The main mechanisms claimed by the companies concerning the electrostatic elements are the following:

- Generation of H^+ and O_2^- ions that agglomerate into clusters with water molecules that further react to form •OH and these can alter the proteins in microorganisms and inactivate them.
- Charging of pollutants by negative ions, which are then collected via electrostatic precipitation.
- Generation of H^+ and O_2^- ions that will attract airborne particles when reforming stable molecules. The agglomerates are then big enough to be trapped by mechanical filters or even "fall to the ground".
- Generation of high-energy electrons that collide with the surrounding air to form different species (excited O_2* and N_2*, •OH, O atoms). The formed byproducts can decompose hazardous pollutants.

For the filters, the HEPA filter is widely used, even after an ionizer. As shown in Table 2, some of the devices even employ electrostatic HEPA filters (*Sharp, Daikin*). This stage of the device is generally filtering all types of biological contaminants and PM above 300 nm. Since the filters accumulate pollutants, they later need to be replaced or cleaned, which can entail extra cost. An alternative solution can be wet scrubbers, as proposed by *Toshiba*, which drains the pollutants with a water flow from the filtering system. But in this case, some of the pollutants are shifted to the water, which in turn would need to be decontaminated. Finally, UV-C lamps, operating between 230 nm and 280 nm, can be added to further increase the efficiency of the system. UV-C lamps are well known to have a strong germicidal effect. They are usually placed close to the output of the device, to kill the remaining biological pollutants, but also to clean the filters, as mentioned by *LG* and *Daikin*.

3.2. Efficiency assessment of commercial systems

In this section, the efficiency of the different systems claimed by the companies is discussed, along with the available data and reports concerning the measurements performed. The pollutants have been divided into three categories:

- VOCs, which cover all the chemical compounds in the gas phase;
- Biological pollutants including bacteria, fungi, viruses and molds;
- Solid or liquid PM, that are small enough to be airborne and inhaled by humans. These are usually allergens, dust or smoke particles, and pollen.

Focusing first on the VOCs, Table 2 shows that six of the companies

Table 2
Non-exhaustive list of companies with IAP system commercially available. For the efficiency, NA stands for non-applicable and ND for not defined. Values in the table correspond to the values given in the company's product advertisement. CADR stands for clean air delivery rate and SIE for specific input energy.

Company	Technology	Pollutant targeted			Efficiency (minimum value)			Power consumption (W)	CADR (m^3/h)	SIE (kWh/m^3)
		VOCs	Biological	PM	VOCs	Biological	PM			
Sharp (Plasmacluster)	Pre-filter, ionizer, deodorizing filter, electrostatic HEPA filter	×	✓	✓	NA	99 %	99 %	40	240	170
LG (Plasmaster Ionizer)	Pre-filter, ionizer, filters (ND), UV-C	×	✓	✓	NA	99.99 %	99.95 %	NA	NA	NA
Mitsubishi (Plasma Quad)	Pre-filter, plasma ionizer, electrostatic filter, deodorizing filter	×	✓	✓	NA	99 %	98 %	NA	NA	NA
Toshiba	Pre-filter, plasma ionizer, electrostatic filter	✓	✓	✓	ND	99.9 %	ND	NA	NA	NA
Daikin (Daikin Streamer)	Pre-filter, streamer discharge, electrostatic HEPA filter, anti-bacterial filter, deodorizing filter, UV-C	✓	✓	✓	ND	99.3 %	99.6 %	15	192	78
PlasmaAir	Bipolar ionizer	✓	✓	✓	80 %	86.6 %	73 %	4.8	10195	0.47
PlasmaCleanAir	Pre-filter, ionizer, electrostatic precipitator, UV-C	×	×	✓	NA	NA	>95 %	800	7560	106
BlueAir	Electrostatic filter, mechanical filter	✓	✓	✓	ND	99 %	>99.97 %	39	335	116
AirOasis	Bipolar ionizer, HEPA filter, activated carbon, silver antimicrobial filter, UV-C	✓	✓	✓	99 %	99.9999 %	99.9999 %	140	1200	117
Oxytec	Pre-filter, volume plasma, activated carbon	✓	✓	✓	99.98 %	97 %	ND	175	460	380

present their product as being able to decompose these contaminants. However, the efficiency is given for only half of them. In the case of *Toshiba* and *BlueAir*, it can be found that the product is efficient at removing VOCs from the indoor air but without any quantification or compound specified. In the case of *Daikin*, the VOC removal concerns formaldehyde and NOx. According to the webpage of the *Daikin Streamer Technology* [100], one study has been performed on the VOC removal, but the report is not available and no additional information is provided.

Oxytec and *AirOasis*, both claim efficiencies against VOCs of at least 99 %. Unfortunately, *Oxytec* does not provide any report or data concerning the quantitative measurements for their device. *AirOasis* provides slightly more details. No methodology is given, but the time evolution of formaldehyde, benzene and trichloroethylene, with an initial concentration of 24 ppm for all of them is shown. The pollutant is found to be reduced by more than 95 % in 22 min, and it takes 403 min to reach 99 % removal for all three pollutants.

Sharp tested the efficiency of their device against polycyclic aromatic hydrocarbons. Measurements were performed in a closed box, in which petri dishes with the different molecules were put as a very thin layer. Their ionizer, called *Plasmacluster ion generator*, generated around 10^6 ions.cm^{-3}, and reactions with the pollutants led to efficiencies of 91.1 % on fluoranthene, 62.1 % on chrysene and 94.6 % on dibenzo(a,h) anthracene. But in this case, it seems that the studied molecules were evaluated as a thin layer rather than as gas phase compounds. Additionally, they were exposed to the ions for 10 days.

The most detailed report about the efficiency against VOCs is from *PlasmaAir* [101]. One of their models (*PA604*) was tested in a real conditions environment, for the IAQ improvement in the trams or Zaragosa (Spain). Measurements were performed after normal operation of the trams, so the indoor air is typical of everyday life in public transport, but in a closed case where no extra air from outside was brought inside. They measured the concentrations of 54 different VOCs over 6 h. A reduction of 80 % was measured, and no new byproducts were detected.

According to Table 2, biological and PM are the main pollutants targeted by the companies for their IAP devices. All of them are efficient against both types of contaminants, except *PlasmaCleanAir*, which provides specialized systems targeting oils, grease and odors for kitchens. For all the devices, high efficiencies are reached. Note that the efficiency given in the table is the minimum value for any pathogens measured. This means that in cases where several contaminants were tested, the efficiency indicated in the table is the lowest one, which does not mean the device is not efficient. For example, the decontamination system from *PlasmaAir* is the one with the lowest efficiency in table (86.6 %). However, they measured the efficiency of two of their systems against 4 bacteria, 4 molds, and 4 viruses. They obtained efficiencies ranging from 86.6 % for Influenza A (H1N1) after 60 min of exposure, up to 99.995 % for SARS-CoV-2 Omicron in 90 min for the viruses. For the bacteria, over 60 min of operation, the most resistant to their device was the *Bacillus subtilis* var. *nigers,* with a reduction of 89.30 %, while they reached 99.99 % of removal for *P. aeruginosa*. For the molds, the minimum efficiency was found to be 90 % for *D. abundans*, and the highest efficiency was found to be against *C. albicans* with 97.69 %. A result is also provided concerning fungi removal (*C. cladosporioides*), but the efficiency is much lower with only 36.27 %. Measurements of $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$ and $PM_{5.0}$ were also performed. Reduction of the number of PMs for each of those ranges were 73 %, 88 %, 86 % and 75 %, respectively. Experimental details are not described here, but most of the measurements have specific reports with complete methodology and are available online. It is also worth mentioning that the efficiency evaluations have been conducted by third party independent entities and following some standards.

Other companies presented in Table 2 have available reports concerning their efficiency measurements for biological and PM pollutants. *Mitsubishi* had their *Plasma Quad* technology (electrostatic element in their devices) tested by several external entities. Biological contaminants, Influenza A and *P. citrinum* were inhibited by 99 % in 2.5 h, while it took more than 5.5 h to reach this level of inhibition for SARS-CoV-2 virus and *S. aureus* bacteria. For the PM, cigarette smoke removal ($PM_{2.5}$) was tested according to standards (JEM1467), while dust (dust and mites) and allergens (cat fur and pollen) were tested using original methodologies. The cigarette smoke was reduced by 99 % in 300 min, and efficiencies higher than 98 % were found for dust and allergens after a single pass in the device. Note that the efficiencies of the device could be higher, since those tests do not include the other elements (mechanical filters).

Sharp has a dedicated webpage with all the reports performed by external institutes on their *Plasmacluster* technology, along with the entities that were performing the tests [102]. On the biological contaminants side, measurements of the efficiency against 7 viruses, 11 different bacteria, and 6 fungi are reported. On their device characteristics website, usually one general value of efficiency is given for one type of pollutant. As an example, the measurements on Influenza A showed a 3-log reduction in the infectivity in 2 h, when exposed to ions density $3x10^5$ cm^{-3}. But the commercial device only produces $2.5x10^4$ ions.cm^{-3}, and in this case the efficiency is lower (95 %). Some information is also provided concerning the cigarette odor removal, which is reduced to "unnoticeable" level in 55 min in a 41 m^3 space, but no data or report is available supporting this statement. Several other reports about different types of pollutants are available but will not be described all in detail here. The important point that should be noted is that the values provided as a general indicator for the efficiency should be taken carefully, as they are not given for a specific target. Indeed, experiments performed with the *Plasmacluster* technology usually depend on several parameters, such as the pollutant tested, the exposure time, and the ion density. Hence, the efficiency against a specific target should be checked individually.

The last company with lots of information and data published regarding their efficiency measurements is *Daikin*. Alike *Sharp*, they have a dedicated website regrouping the reports [100]. Again, it is worth noting here that those reports refer to the *Daikin Streamer Technology, i. e.*, only the electrostatic element, and not the whole purifying device. The technology has reported tests against 13 viruses, 11 bacteria, 1 mold, and 21 types of allergens. As the results will not be detailed individually, for the viruses, any pathogen tested shows at least a 2-log reduction after times ranging from 1 h to 8 h. Similarly, most of the bacteria targeted were inactivated up to 99.9 %, but depending on the bacteria, the treatment time was extended up to 24 h of exposure to the device. Only one mold was tested, *C. cladosporioides*, but it also reached a 3-log reduction after 24 h. For the allergens, the values found for the efficiencies are broader. For mites, a reduction of 96.9 % was observed after 4 h of irradiation. The effects against 16 types of pollen were evaluated, and the values range from 80.6 % for Orchard grass up to 99.9 % for Timothy grass. In this case, exposure times were much longer, varying from 2 to 4 weeks. Finally, one measurement for PM was also performed, combining allergens, exhaust gas (diesel exhaust particles) and PM 2.5 particles (not defined). Here, the allergenic strength is given rather than the efficiency. After exposure for 48 h to the streamer irradiation, the allergenic strength was reduced by 92.4 %. Note that all the measurements were also performed by external entities.

All the other devices listed in Table 2 do not have reports dedicated to the evaluation of the performance of the system, or they mention reports which cannot be found online. *Toshiba* states an efficiency of 99.9 % against bacteria of their device, as well as the decomposition of smoke, ammonia, volatile organics, food smells and bad odors, the inhibition of molds and fungi formation, and the elimination of airborne viruses such as avian flu (H5N1). Antibacterial and antiviral properties are mentioned to have been tested by two different agencies, but no data is available to support the provided assertions.

PlasmaCleanAir, provides a commercial system for kitchens for oil, grease and smoke removal. They estimated the efficiency of the system to be 95 %, for measurement performed according to the ANSI norm ASHRAE 52.2 (title of the norm: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size). They also provide a calculated estimation of 99 % efficiency for double pass configuration.

LG also provides some values for the efficiency measurements performed by an external company along with the reports number, but the latter cannot be found online. Still, they measured a reduction of *E. coli* by 99.9 % in 30 min and 99.6 % for *S. aureus* in 60 min. The decrease of smoke odor intensity is also evaluated and reduced from 3.6 to 1.5 in 60 min. Finally, they assert air purification of 99.99 % in 30 min, without any specific target, but this result is contradictory with the previous efficiencies where lower values can be found for specific pollutants in longer times.

BlueAir presents their system as being able to kill 99 % of germs, and remove dust, pollen, dander, mold, VOCs and odors. Their results are based on removal testing of PM 2.5 (0.1–2.5 μm) and germs (H1N1, *E. coli*) up to 90 min in a 30 m^3 room. But again, no data is published concerning those measurements.

AirOasis provides more information about the results obtained for their device. No methodology is given about how the measurements were performed, but several graphs present the efficiency as a function of time for 1 virus, 5 molds and 3 bacteria. A 4-log reduction was measured for H5N1 in only 20 min. For the 5 molds tested, a 5-log reduction was observed for all of them in 30 min, and a further 6-log reduction was achieved in 180 min. For the same time, i.e., 30 min and 180 min, the tested bacteria were reduced by 99.99 % and 99.9999 %, respectively.

The last company of the list is *Oxytec*. This startup proposes air cleaners that are claimed to be the only ones employing a volume plasma as a decontamination medium. Their system allows to reach efficiencies of 99.98 % against VOCs and 98 % against biological contaminants. The reports are only available on demand, and only the one concerning the biological pollutants removal was provided. Their test was performed according to DIN-ISO-16000-36 on airborne viruses (Phi6 bacteriophage). The performance evaluation was also done without a fine particle filter, which could increase the efficiency of the complete system. O_3 measurements were also performed and 10 μg m^{-3} were produced during operation, which remained lower than the legal limit (120 μg m^{-3}).

Finally, the last relevant information retrieved from those companies is the power consumption of their device, along with the clean air delivery rate (CADR), i.e. air flow rate. From these two parameters, it is possible to calculate the specific input energy (SIE), which is the ratio of power consumption to the CADR, and represents the energy brought to a given volume of gas passing in the device. As shown in Table 2, both the power consumption and CADR cover a broad range of values. In most cases, higher power consumption allows to operate at higher CADR, which is reflected on the SIE where most values are around 100 kWh/m^3, whatever the power and CADR. The efficiencies of devices reaching such SIE values are all similar, but since they are combined with filters, it is complicated to infer the impact of the SIE on the efficiency. Still, two cases are noteworthy in the list. The first one is the company *PlasmaAir*, for which the device is the one with the lowest power (4.8 W) and highest CADR (10195 m^3/h), leading to a SIE of only 0.47 kWh/m^3. Since the device is, up to the available information, only composed of a bipolar ionizer, the power is quite low. This can also be the reason why for some pollutants, the efficiency reached is lower than by other devices, along with the high CADR. The second one is *Oxytec*, which is the company that was mentioned to be using a volume plasma discharge, and not just an ionizer. In their case, the device achieved a SIE of 380 kWh/m^3. This is more likely due to the type of discharge used, which might have higher current than ionizers and hence higher power consumption, but in this case, even without any HEPA filter, they still managed to achieve high efficiencies for VOCs and biological contaminants.

This section intended to review the existing commercial devices, along with the technology they used and their overall chemical and biological efficiency. Only devices with at least one electrostatic element were selected. It is reminded here that the list is not complete and other commercial products are available on the market. But as already stated, we mainly focused on bigger companies with a long history on the market employing proven technologies. It was seen that in most cases, the devices employed several decontamination technologies, the most frequent being mechanical filters along with an electrostatic element which is dominated by ionizing systems. 40 % of the devices also incorporated UV radiation for further decontamination or cleaning. In terms of mechanisms that are claimed by the companies to be the ones governing the destruction of the pollutants, the charging followed by electrostatic collection, and the creation of oxidative species, mostly •OH and O_2^-, breaking chemicals into smaller byproducts and inactivating pathogens, were the most cited.

The next part discusses the limitations of those systems as well and the information available from the manufacturers concerning the commercial devices.

3.3. Limitations and perspectives

As presented in the previous section, very efficient commercial devices already exist on the market for IAP. Some limitations and unknowns of the devices are discussed in this section.

Concerning the technology itself, especially the electrostatic element, it is sometimes unclear what type of source is used for decontamination. For example, not many details are provided concerning the geometry or the electrical circuits used for generation of the ionized medium. More details can usually be found in the patents related to the products, but those are usually not easily retrieved. Several patents were still found (*PlasmaCleanAir* patent #US9908082; *Sharp* ionizer patent #US9005529; *LG* ionizer patent #US9263858; *PlasmaAir* bipolar ionizer patent #US10111978; *Daikin streamer* patent #US11318478). Most of them present the technical details of the device, but they contain minimum data on their properties. For example, more consistent sets of data about the amount of positive and negative ions generated by the source could be of interest to compare the systems and the effect of ion densities on the decontamination efficiency.

It has been mentioned several times already that these IAP systems usually employ a combination of different technologies. However, tests were performed either on the electrostatic element (as for example for *Mitsubishi* and *Daikin*), or on the whole device (others). This makes comparison complicated, not only when one wants to compare two different devices, but also if one wants to compare them with results obtained for lab-scale experiments reported in scientific papers. A way to homogenize data for all these systems could be the use of standards and norms for the assessment of the performance of the devices. A recent review published by Saffell et al. [103] presents the requirements for the improvement of IAQ through standardization [102]. Such guidance and normalization, especially with the international standards ISO 16000 series, can help in this sense and allow a systematic characterization of the commercial systems.

Another point that should be mentioned is the identification of the compounds that are targeted by the devices. As shown, more than half of the devices presented in Table 2 are efficient at removing VOCs. Looking into more details, very little information is given about which VOCs are targeted and what are the methods of their measurements. More generally, it can be complicated to make proper comparisons of the efficiency of two devices if the pollutants, their type, number and concentration are different. Transparency concerning the measurements is important to have a better understanding of the capacity of the devices and can help the customers to make the right decisions depending on their needs.

Electrostatic elements and especially ionizers are present in many devices. Indeed, their capacity to generate ions and radicals allows them to remove the VOCs and inactivate or destroy biological contaminants. However, almost all the devices still use mechanical filters. The combination of the two technologies more likely allows the mechanical filters to have a prolonged lifetime. Yet, those filters still need to be changed at some point, which can create secondary pollution if the accumulated pollutants are not inactivated, for example with UV lamps, but also additional costs for maintenance, both for changing the filters and the UV lamps. Ideally, future technologies need to get rid of both those secondary pollution sources and additional costs. Limiting the number of elements in the system can also lead to more robust devices, with a lower risk of having one of the several components that fail. Additionally, both HEPA filters and ionizers, although they have demonstrated their efficiency, are already quite old technologies. Over the last decade, plasma combined with catalysts have demonstrated to be a promising technology. Their efficiency against many different types of pollutants has been proven, even at high concentrations. Their use and scaling up to commercial systems have huge potential for future applications in indoor air cleaning, and some small companies have already started to develop such systems. The next section presents a review of the recent work and progress achieved in the laboratory environment for those systems.

4. Recent advancement in plasma and catalyst for IAP

4.1. Introduction of plasma-catalyst technology and overview of lab scale tests

4.1.1. Plasma-catalytic mechanisms

The potential of NTP technology as a viable solution for the treatment of various gaseous pollutants has already been proven. The NTP process is widely recognized for its ability to generate reactive species, including O_3, H_2O_2, •OH, and •O. These species play an important role in the oxidative breakdown of biological and chemical contaminants, especially VOCs. Nevertheless, the utilization of NTP in the degradation of these contaminants is associated with certain drawbacks, primarily attributed to the generation of undesirable by-products that may restrict its potential indoor air applications [80].

Plasma can be utilized more efficiently by exploiting its synergistic effects when integrated with heterogeneous catalysts using various metal (such Pt, Pd, Ag, Ni) or metal oxide catalysts (such as TiO_2, MgO, $BaTiO_3$ etc.), often with photocatalytic properties. A photocatalyst becomes active when it absorbs photon energy (*hv*) equal to or greater than the bandgap energy between the valence band (VB) and the conductive band (CB). This activation leads to the formation of negatively charged electrons (e^-) and positively charged holes (h^+) pairs [104]. While it is true that NTP itself can produce UV radiation, the photon flux it emits is insufficient to have a meaningful impact on the activation of catalysts, as extensively documented and proven in multiple studies [105–108]. Sano et al. [109], showed that the contribution of photocatalysis induced by UV light from the surface discharge plasma on the acetaldehyde decomposition is estimated to be less than 0.2 %. But it is well known that electrons in NTP can reach temperatures of 1–10 eV, therefore, in a plasma-catalysis system, electrons with an energy greater than band gap energy can generate ($e^- - h^+$) pairs on the surface of the catalyst. For example, when a photocatalyst is introduced into an NTP reactor, the generation highly energetic electrons by the plasma can induce photocatalytic reactions through the following path producing $e^- - h^+$ pairs:

$$photocatalyst + plasma\ (high\ energy\ electrons) \rightarrow e^- + h^+ \tag{1.1}$$

$$h^+ + H_2O\ (ads) \rightarrow H^+(ads) + \cdot OH\ (surf) \tag{1.2}$$

$$e^- + H_2O\ (gas) \rightarrow \ \cdot OH\ (gas) + \cdot H\ (gas) + e^- \tag{1.3}$$

Adsorbed water vapor reacts with surface-localized VB hole to generate surface bound •OH (eq. (1.2)) [110]. This process is similar to the action of UV excitation. Direct gas-phase reaction also occurs between electrons and H_2O molecules, but this reaction is generally ignored in conventional photocatalysis due to the low cross-section [111]. However, in the plasma-assisted systems, the generations of high-energy electrons enable the dissociation of water molecules in the gas phase and the generations of gas-phase •OH takes place (eq. (3)). The generation of $e^- - h^+$ pairs, which enables the subsequent redox reaction, is regarded as the primary and crucial stage of photocatalytic processes. The electrons and holes generated by photocatalytic process react with the adsorbed O_2 and H_2O molecules in their vicinity, forming adsorbed $\bullet O_2^-$ and •OH. After a series of reactions, the $\bullet O_2^-$ will afterwards generate surface bound •OH (eq. (1.5)–(1.7)).

In a heterogeneous photocatalysis mechanism, two reaction steps happen successfully:

- The reduction of O_2 by the electrons (from CB) and •OH are generated via a series of reactions, as follows:

$$e^-_{CB} + O_2(ads) \rightarrow O_2^{\cdot -}(ads) \tag{1.4}$$

$$O_2^{\cdot -}\ (ads) + H^+\ (ads) \rightarrow HO_2^{\cdot}\ (ads) \tag{1.5}$$

$$HO_2^{\cdot}\ (ads) + HO_2^{\cdot}\ (ads)\ \rightarrow\ H_2O_2\ (ads) + O_2\ (gas) \tag{1.6}$$

$$H_2O_2\ (ads) + e^-_{CB}\ \ \rightarrow\ \cdot OH\ (surf) + OH^-\ (ads) \tag{1.7}$$

- The holes (from VB) transform the H_2O molecules into •OH.

$$h^+_{VB} + H_2O\ (ads) \rightarrow\ \cdot OH\ (surf) + H^+ \tag{1.8}$$

These gas-phase and surface-bound •OH act as an oxidizing agent and change toxic biological/chemical compounds (gas-phase/adsorbed) into CO_2, H_2O and other unharmful by-products. Plasma-driven catalytic technology has shown great promise in air purification, demonstrated by its ability to achieve higher mineralization efficiencies while concurrently minimizing the generation of undesirable by-products [112,113]. The combination of NTP with catalysts has been found to enhance the production of many active species, including •OH, and improve the activity (by enhancing adsorption and activation, restoring active sites, etc.) and stability (by preventing thermal degradation, removing carbon deposits, etc.) of photocatalytic materials [114].

Now, a crucial question arises: how can catalyst and NTP be combined? Two arrangements exist [112]:

- Two stage-stage system, where the catalyst is introduced upstream/downstream of the plasma discharge region. More usual is the system with catalyst following the plasma, also known as post-plasma catalysis (PPC) system.
- The single-stage system, where the catalyst is introduced directly in a plasma discharge zone, also known as in-plasma catalysis (IPC) system. This introduction leads to heterogeneous reactions within the system due to the interaction between the catalyst and the plasma.

The use of the IPC arrangement allows the catalyst to interact and be directly activated by plasma, short-lived species and UV radiation, thereby influencing the chemical process. In contrast, in the PPC arrangement the catalyst interacts only with long-lived species and pollutants pre-treated by the plasma [112].

The PPC arrangement is easier to set-up and control, as the plasma and the catalyst systems can be tuned individually. The IPC is more complicated as the plasma and the catalyst mutually affect each other, and their common tuning is elaborate and often limited. However, a precisely tuned IPC arrangement may lead to synergistic effects of plasma and catalyst with substantially higher efficiencies compared to PPC. Fig. 3 provides an overview of key plasma-catalytic processes explored in this review. The integration of catalysts within the plasma discharge can modify discharge characteristics and alter the energy distribution of accelerated electrons [115]. These changes further impact the formation of transient reactive species, such as O, $\bullet O_2^-$, and OH radicals. While many of these species are short-lived, some recombine into more stable compounds like O_3, which can migrate to contamination sites and enhance degradation. Additionally, the highly reactive plasma environment induces structural and chemical

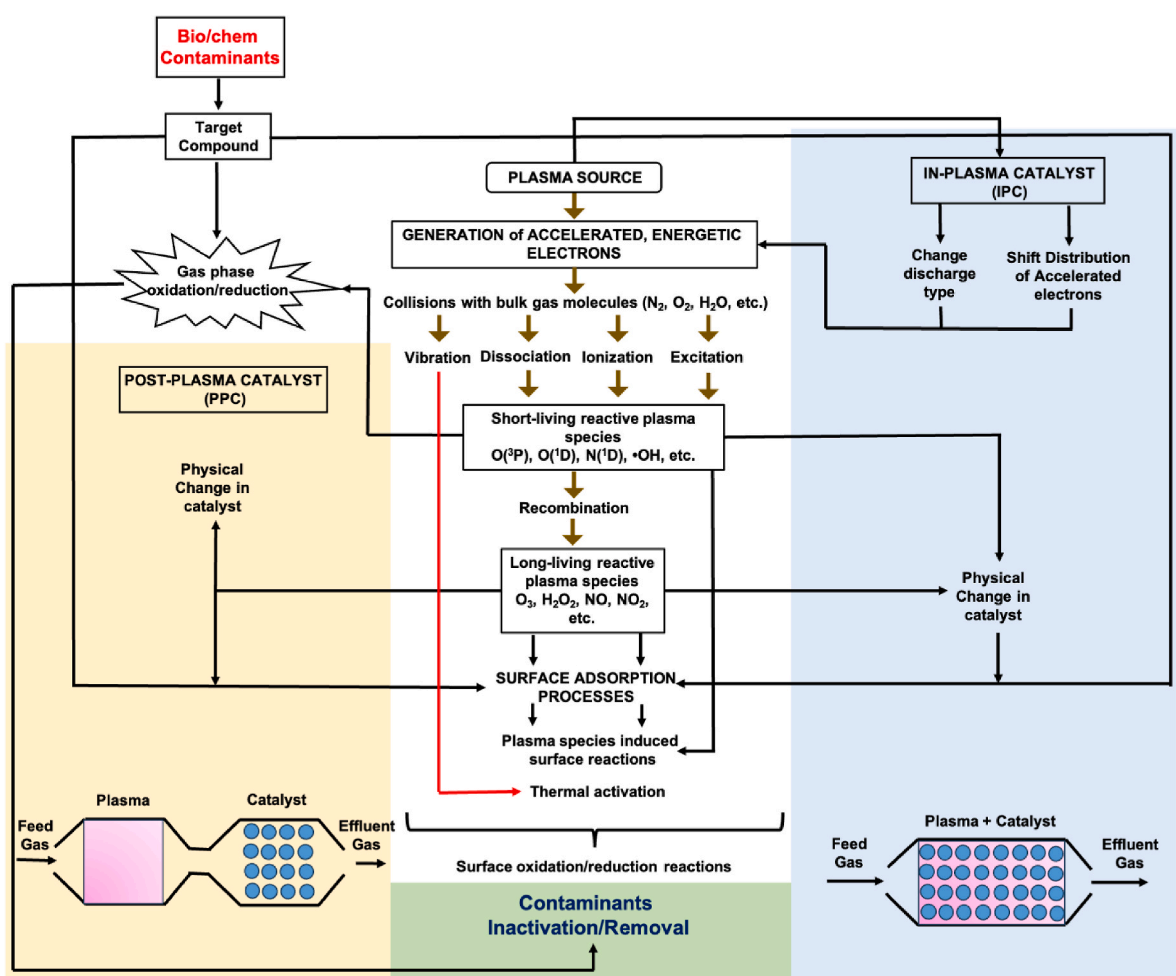

Fig. 3. Overall insights of plasma-catalytic mechanisms.

modifications in the catalyst, influencing its pollutant removal efficiency [116]. Notably, plasma-catalytic systems often follow zeroth-order kinetics, underscoring the dominance of surface-mediated reactions in the decomposition process.

The catalysts integrated in plasma discharges can manifest in various forms, including coating on reactor walls or electrodes, fibers, porous foams, honeycomb monoliths, granules or pellet beds [71,117–119]. Incorporating catalysts in the plasma reactor plays a vital role in the IPC arrangement overall efficacy. Nevertheless, it is essential to understand the precise method of introducing the catalyst into the NTP reactor to enhance its performance. It is crucial to determine the appropriate catalyst based on both its chemical composition and its structural properties. The catalyst can exist in a powdered state and macroscopic forms, including pellets, spheres, honeycombs, foam and sheets [120–122]. The selection of catalyst housing in the NTP reactor is contingent upon the specific reactor type, whether it belongs to the surface DBD, packed bed discharge, or microwave discharge category. From now on, our discussions will be limited to the IPC system to gain a clearer understanding of discharge behavior in NTP reactors.

4.1.2. Catalyst integration and discharge behavior in plasma reactors

Catalysts, typically employed as pellets, granules, or fibers, are placed within the plasma reactor, either partially or fully occupying the discharge zone. A fully packed reactor drastically alters the discharge mode by reducing the available discharge volume, shifting the behavior from filamentary discharges to localized micro-discharges and surface discharges along the catalyst. In contrast, a partially packed reactor retains strong filamentary discharges while still promoting enhanced plasma-catalyst interactions [112]. The choice of the catalyst material significantly influences the plasma generation. For instance, dielectric materials like TiO_2 and $BaTiO_3$ intensify the plasma formation due to their polarizability, increasing the local electric field strength near contact points [123]. This effect arises from the shortened discharge gap and the non-uniform electric field distribution created by high-dielectric-constant pellets (e.g., $BaTiO_3$ or $NaNO_2$). Kim et al. [124, 125] investigated Ag catalysts supported on TiO_2 and γ-Al_2O_3 and found that partial discharges occurring at the contact points between neighboring catalyst particles significantly influenced the development of primary streamers. These partial discharges, when initiated ahead of the primary streamer, effectively directed the streamer's path through the discharge region. Additionally, it was observed that the dielectric constant of the catalyst beads played a role in the timing of partial discharge initiation, higher dielectric constants led to earlier discharge formation. Some studies also reported that packing materials with high dielectric constant are not good for the surface streamer [126]. The shape and surface area of the catalyst also plays a vital role in plasma discharge and overall reaction performance in plasma-catalytic processes. For example, a higher surface area provides more active sites for plasma-catalytic interactions, leading to enhanced reaction, adsorption and conversion rates [127].

Additionally, the structure (microstructure and nanostructure) of the catalyst also plays a critical role. Nanostructured catalysts (materials with nanoporosity or nanoparticles size) accelerate micro-discharges at the nanoscale, while catalysts with larger pore sizes (e.g., ceramic foams) produce strong electric fields within the pores, further changing the discharge characteristics [113]. Research findings show that the integration of a catalyst not only enhances the synergy between plasma and catalyst, but also fundamentally transforms the discharge behavior and consequently improves reactor performance.

The integration of plasma and catalyst often yields enhanced results, a phenomenon widely described as a synergistic effect [128–130]. This effect implies that the combination of plasma and catalyst leads to performance improvements (in terms of degradation) greater than their independent effects, thereby generating considerable interest in practical applications. Assadi et al. [131] made key contributions to this field, showing synergistic behavior in different conditions of trimethylamine degradation using a DBD plasma-photocatalysis system. They attributed it to factors such as the activation of TiO_2 by plasma-generated UV radiation and improved by-product desorption due to reactive species.

Further evidence of this synergy comes from Zhu et al. [132], who investigated toluene removal using an $Au/CeO_2/Al_2O_3$ nanocatalyst and plasma. While standalone plasma treatment achieved only 5 % toluene removal and the catalyst alone reached 67 %, their combined led to nearly total elimination, with mineralization efficiency approaching 90 % (see Table 3). Pan and Chang examined a La_2CoMnO_6 perovskite catalyst in a packed-bed DBD reactor and found that while the catalyst alone was inactive below 150 °C, its integration with plasma enabled complete toluene removal and 96.8 % mineralization efficiency [133]. Studies compiled in Table 3 demonstrate the effect of introducing catalysts into the plasma region, as well as the individual and synergistic impacts of plasma alone, catalyst alone, and their synergistic effect on the decomposition of various VOCs. It was also observed that introducing a catalyst into the plasma discharge zone often reduces the byproduct O_3 formation [134,135]. For instance, Zadi et al. [135] investigated the impact of NTP and TiO_2 photocatalyst on the indoor air treatment of a refrigerated food chamber, using benzene and propionic acid as a target pollutant. They observed that the combination of NTP and TiO_2 significantly reduced the O_3 formation, from 21 ppm in plasma alone to 6 ppm in plasma-catalytic systems.

The synergistic interactions between plasma and catalysts in NTP-DBD reactors present considerable complexity, as illustrated in Fig. 4 [136]. Researchers employed many advanced diagnostic techniques to understand these complex processes, such as optical emission spectroscopy, X-ray photoelectron spectroscopy, Fourier transform infrared spectroscopy, etc. for probing gas-phase reactive species, and perform surface chemical analysis and surface-adsorbed intermediates. Furthermore, to validate the experimental findings and predict the behavior of complex plasma-catalytic systems, computational modelling serves as a powerful tool.

4.2. Introduction of plasma-catalyst technology in pilot scale and industrial solutions focused on IAP

As the integration of NTP and catalysts is getting more attention for exhaust gas cleaning, many researchers also explored this approach for IAP. As discussed in the previous section, there are many types of indoor air pollutants (chemical, biological, particulate matter etc.) that need to be addressed, as they pose potential hazards to humans in indoors environments. Various methods (such as DBD, ESP, PCO, corona discharge etc.) have been employed for the removal or inactivation of these pollutants, but there is still significant scope for further research in the field of plasma-catalyst systems for IAP.

These methods rely on direct and indirect plasma treatment. In direct treatment, pollutants are directly exposed to the plasma and plasma-generated reactive species in a flow system, where oxidative reactions take place, leading to the decomposition/inactivation of the pollutants. However, in the case of indirect treatment, the pollutants react with the reactive species after the plasma discharge region in a flow system, or they are treated in a reaction chamber where the plasma source is housed. In this approach, the contaminants do not come into direct contact with plasma discharges.

As an example of direct treatment, Lai et al. [137] investigated the effect of cold plasma in a ductwork system with a flow velocity of 7.0 m s^{-1} and analyzed the impact of negative air ions on five different types of bacteria, namely *E. coli, P. alcaligenes, S. epidermidis, M. luteus* and *S. marcescens*. For the first three types of bacteria the inactivation varied from 20 % to 70 %, while no detectable inactivation was found for the other two. Pemen et al. [138], proposed a novel plasma-catalytic technology that uses a SDBD source and plates coated with Al_2O_3, placed parallel to the SDBD plates. They used Al_2O_3 plates with TiO_2 and tested different combinations of Al_2O_3 and SDBD plates to study the conversion

Table 3
Literature highlighting the synergistic effect of plasma and catalyst for the VOCs decomposition.

Discharge/Reactor type	Catalyst	VOCs	Initial concentr. (ppm)	Ozone (ppm)	Flow rate (L/min)	Conversion (%)			Reference
						Plasma alone	Catalysis alone	Combined	
DBD/Cylindrical quartz tube	$SrTiO_3$/rGO UV	Toluene	100	–	3	90.9	3	100	[147]
DBD/Co-axial cylindrical	TiO_2/GFT UVA	Trimethylamine	57	215[a] 150[b]	33–166	39	34	91	[131]
DBD/Cylindrical quartz tube	SiO_2–TiO_2 UVA	Propanoic acid	3.24	21[a] 6[b]	33	35	50	96	[135]
DBD/Co-axial cylindrical	TiO_2/GFT UVA	Ammonia	50	30[a] 23[b]	33	20	51	80	[134]
DBD/Co-axial cylindrical	TiO_2/GFT UVA	Butylaldehyde	50	30[a] 23[b]	33	7	28	40	
DBD/co-axial cylindrical	Au/Ce_2O_3/Al_2O_3	Toluene	100	–	0.2	67	5	100	[132]
Corona discharge/Wire cylinder packed	Pt/Al_2O_3	Butylacetate	120	–	20	10	18	42	[148]
DBD/fixed-bed quartz	La_2CoMnO_6	Toluene	150	–	1.2	82	0	100	[133]

[a] Ozone concentration in plasma alone.
[b] Ozone concentration in the presence of catalyst.

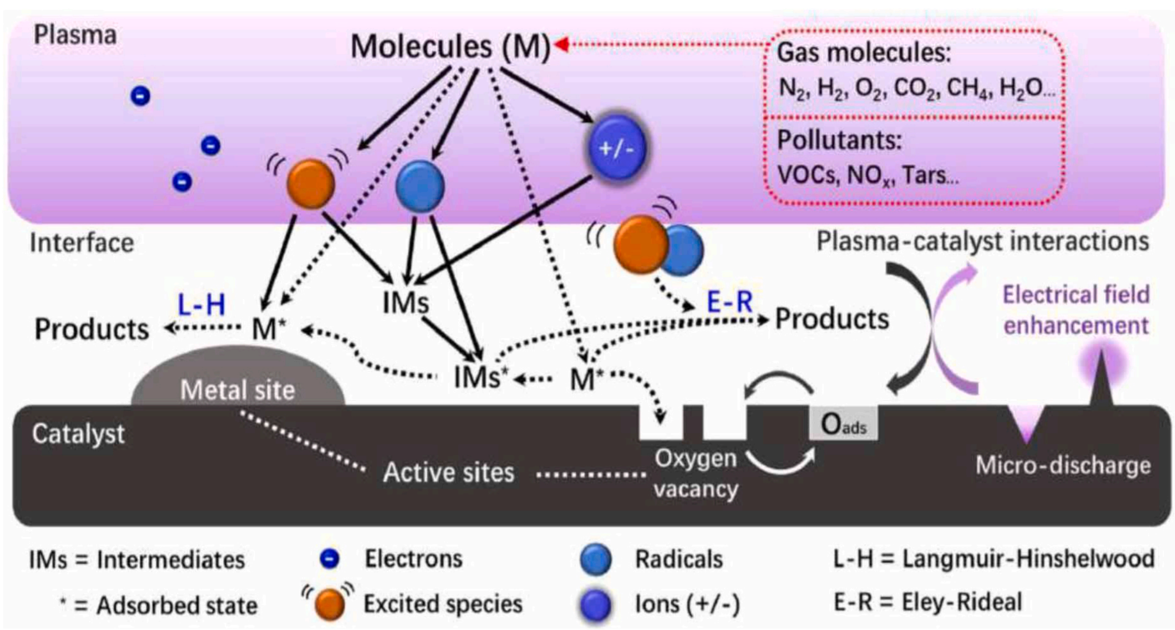

Fig. 4. A brief overview of the species and key mechanisms in the plasma-catalytic surface interactions. Reprinted with permissions from Ref. [136].

of NOx and ethylene. They found that with increasing initial concentration of NOx, the conversion efficiency decreased, and a longer residence time (i.e., low flow rate) was required to achieve higher conversion efficiency.

In an indirect treatment method, Diaz et al. [139] treated $PM_{2.5}$ using multi pin corona discharge (MPCD) and DBD in a refrigeration chamber. In comparison to DBD, the MPCD generator was found to have higher removal efficiency of $PM_{2.5}$, with less ozone concentration and energy consumption. As another example of indirect approach, Jangra et al. [71,85,140,141], employed a DBD plasma reactor in conjunction with TiO_2 nanoparticles catalyst for the treatment of biological and chemical pollutants. They observed that the synergistic effect led to almost complete inactivation/decomposition of both biological (e.g., *E. coli*, MS2 bacteriophage, and ESCAPE bacteria) and chemical pollutants (e.g., toluene and benzene).

Various studies were performed for the decomposition/inactivation of various biological and chemical indoor air pollutants by using direct and indirect approaches (with DBD, ESP, PCO, corona discharge etc.). For example, Tanski et al. [142] used a SDBD-driven two-stage electrostatic precipitator (electro hydrodynamic as an alternative discharge source and SDBD as a bipolar ion generator). They proposed that in the two-phase ESP the SDBD would be capable of generating bipolar (negative and positive) ions in the air, which can charge the suspended particles positively or negatively. Simultaneously, the electrohydrodynamically (EHD) induced airflow either boosts or replaces the need for mechanical fans to move air through the system. As a result, the bipolarly charged particles agglomerate and turn into larger charged particles, which can be easily collected when subjected to the electrostatic force in the collecting plate. This dual function of charging and air-moving capability makes SDBD-based EHD actuation a promising replacement discharge source in small-scale or portable ESPs.

Van Durme et al. [143] investigated IPC and PPC systems for IAP by introducing TiO_2 into the plasma reactor and positioning $CuOMnO_2$/TiO_2 in a post-plasma configuration. They observed that this combination reduced the O_3 outlet concentration by a factor of seven. In dry air, introducing $CuOMnO_2$/TiO_2 in the post-plasma position resulted in up to 40 times higher toluene removal efficiency compared to non-catalytic plasma oxidation. Ge et al. [144] utilized NTP and NTP-MnO_2 air cleaners for the removal of low concentration of benzene from indoor air. At a fixed discharge power of 9W and a RH of 20 % the benzene conversion efficiency increased from 82.9 % to 89.6 %, CO_2 selectivity increased from 38 % to 80 %, while the concentration of O_3 and NO_2 decreased from 25.3 ppm to 1.3 ppm and from 234 ppm to 25.7 ppm, respectively.

Zeng et al. [145] investigated the effectiveness of ESP combined with catalytic decomposition for the removal of indoor-air pollutants (such as PMs and total volatile organic compounds (TVOCs), and formaldehyde) in an enclosed chamber of 3 m^3. They showed that the ESP removed 94–100 % of PMs, while UV-catalysis achieved 100 % removal of TVOC, including formaldehyde within 20 min of treatment (see Table 4). In another study, Asilevi et al. [73] demonstrated the complete decomposition of low concentrations of formaldehyde (as an indoor air pollutant) using strong ionization NTP reactor operating at a very low power of just 0.8 W.

The transmission of bacteria and viruses over long distances through indoor air can lead to adverse health effects. NTP reactors are increasingly being explored for their potential in the inactivation and elimination of aerosolized microorganisms in enclosed environments. In this context, Xia et al. [72] utilized a DBD-based packed-bed plasma reactor for the inactivation of aerosolized MS2 phage. They found that at an air flow rate of 170 L min^{-1}, approximately 2.3-log reduction of MS2 phage was achieved (2.0-log inactivation + 0.3-log physical removal due to packed bed). Increasing the flow rate from 170 L min^{-1} to 330 L min^{-1} did not significantly enhance virus inactivation. A study by Prehn et al. [77] showed an 89 % reduction of airborne *E. coli* K12 when subjected to DBD combined with ionic wind at a flow velocity of 4.5 m/s (treatment time: 15 s). They used a duct flow system and concluded that the inactivation of microorganisms was influenced by the size of the plasma treatment area and plasma intensity.

Vazquez et al. [146] tested the reduction of formaldehyde as a VOC representative and bio-aerosol with *E. coli* bacteria in a two stage DBD plasma – TiO_2 photocatalyst, both as direct and indirect systems. They tested a single pass of the contaminated air at large air flow rate (250 L min^{-1}). The direct plasma treatment yielded to higher efficiencies. While formaldehyde removal at these conditions reached maximum 40 %, the bio-aerosol inactivation resulted in a reduction higher than 3-log, up to complete inactivation. Their proof-of-concept demonstrates a promising approach of the combined NTP-PCO for scalable commercial IAP.

Table 4 summarizes the different approaches used for the decomposition/inactivation of various biological and chemical indoor air pollutants.

Table 4
Different reactors for the decomposition/inactivation of different indoor air pollutants.

Reactor type	Pollutant	Power consumption (W)	Power Source	Treatment time (min)	Removal efficiency (%)	Flow rate	Catalyst	Reference
Corona discharge	Toluene	–	DC	–	82 ± 2	10 L/min	TiO_2 (IPC) and $CuOMnO_2$/TiO_2 (PPC)	[143]
SDBD	NOx and ethylene	48	pulse transformer with μs duration	–	99.99 (at different energy densities)	5 L/min	Al_2O_3-TiO_2	[138]
DBD	Formaldehyde	0.8	pulse power zero-voltage switching flyback transformer	30	100	0.2 m^3/h	–	[73]
Corona discharge	Benzene	9	DC	90	89.6	–	MnO_2	[144]
ESP and Photocatalytic Oxidation (PCO)	PMs, TVOC (formaldehyde)	9	–	30 20	94-100, 100,	120 m^3/h	MnOx/TiO_2	[145]
PCO	methyl ethyl ketone (MEK)	–	–	–	62.2 36.3	20 L/min 12 L/min	TiO_2/ACF TiO_2/NFF	[149]
SDBD/ESP	$PM_{2.5}$	–	AC	90	~99.5	5.0 m/s	–	[142]
DBD & Multiple corona discharge	$PM_{2.5}$	–	AC	420 and 144	100	–	–	[139]
DBD/cold plasma	*E. coli,* *P. alcaligenes* *S. epidermidis* *M. luteus* *S. marcescen*	4	AC	–	~70 ~65 ~55 ~5 ~3	7.0 m/s	–	[137]
NTP (plasma shield)	*E. coli* *S. epidermidis,* Bacteriophage MS2 *Cladosporium* sp	–	AC	–	99.99 % 99.97 % 99.99998 99.999	28.3 L/min	–	[150]
NTP-DBD	MS2 phage	2.08	AC + 30 kV Neon transformer	–	2.3 log (2.0 inactivated + 0.3 physically)	170 L/min	Borosilicate	[72]
DBD + ionic wind	*E. coli* K12	1.9	AC + DC	15 s	89	4.5 m/s	–	[77]
Cylindrical DBD	*E. coli* MS2 phage Toluene Benzene ESCAPE bacteria	3.3	Pulsed DC	60 30 60 60	99.99 (both) 99.7 74.8 99.9	–	TiO_2	[71] [141] [140]
DBD + TiO_2 PCO	Formaldehyde *E. coli*	22–102 W	AC	2.28 s	40 >3 log	250 L/min	TiO_2	[146]

5. Conclusion and perspectives

Indoor air quality (IAQ) has become an emerging issue, since most humans spend almost 90 % of their time in indoor environments. Indoor air often contains various types of contaminants within three main categories: biological, volatile organic compounds (VOCs), and particulate matter (PM) of various sizes (ultrafine to fine particles). The long-term exposure of humans to these contaminants, even at low concentrations, bring discomfort, results in various health issues, eventually diseases, and low work efficiency.

The first part of this review provides an overview of existing technologies, both destructive and non-destructive, for removing these contaminants from indoor air. Non-destructive ones that trap or shift the pollutants into solid or liquid media, include HEPA filters, adsorption, electrostatic precipitation (ESP), and air ionizers. Destructive methods that partly decompose or fully mineralize pollutants, include bio-filtration or botanical air purification, ozonation, UV photolysis, nonthermal plasma (NTP), photocatalytic oxidation (PCO), and the combined plasma-catalyst systems. Although these technologies are well established, they typically target only one or two groups of contaminants and are not able to remove all of them simultaneously. In the literature, combinations of these technologies have been studied, especially involving the well-established technologies, i.e., HEPA filters, ionizers, ESP, and UV radiation. The combination of those technologies usually allows to remove contaminants that are not targeted by a single technology while reaching higher efficiencies for those already targeted. Extending this research towards combining plasma-(photo)catalyst systems with other technologies would be of interest for their potential future integration into commercial devices.

A novel and very important part of this review is a detailed critical comparison of commercially available indoor air purification (IAP) devices. Despite the limited available data from their manufacturers, a comprehensive table provides a list of key manufacturers and their devices, the targeted contaminants, their decontamination efficiencies, and the typical power requirements and air flow rates. Generally, commercial systems utilize a combination of mechanical filters (like HEPA), electrostatic elements (such as ionizers), and additional components like UV-C lamps to enhance pollutant removal efficiency. Some combine pre-filters, electrostatic precipitators, HEPA filters, and UV-C sterilization to target a broad spectrum of contaminants, including biological ones, PM, and VOCs. While many systems claim high efficiencies against biological pollutants and PM exceeding 99 %, data for VOC removal is less comprehensive and often lacks detailed measurement reports. The limitations of these systems are also discussed, along with their calculated specific input energies (SIE) which are typically around 100 kWh.m^{-3} but may range from 0.47 to 380 kWh.m^{-3}.

These conclusions underscore the current state of commercial IAP technologies, emphasizing their multi-faceted design, varying levels of demonstrated efficacy, and the importance of comprehensive testing data. Additionally, several drawbacks such as the frequent replacement of filters or UV-C lamps, the secondary pollution due to the accumulated contaminants, or the additional costs for maintenance require new solutions.

The last part of the review is hence focused on the ongoing research of nonthermal plasma-(photo)catalysis systems, which is a promising solution to replace or complement the current IAP technologies in commercial devices. The main mechanisms of plasma-catalyst interaction are presented along with the recent literature review. The integration of plasma and catalyst often yields to enhanced synergistic results. The synergistic interactions between plasma and catalysts in NTP reactors present considerable complexity, which is still not completely understood.

The final part of the review discusses the new perspective on the introduction of plasma-catalyst technology in pilot scale and industrial solutions focused on IAP. Various pioneering studies reported that NTP combined with (photo)catalysts is a promising destructive technology that could efficiently target all types of contaminants, especially hard-to destroy VOCs, in addition to the very high efficiency of the removal of bio-aerosols. Various plasma-catalytic devices have proved scalable for large air flow rates and efficient even for a single pass of the contaminated air through the device. By identifying key factors that influence their efficiency and safety, this review outlines a promising foundation for further research and technological development in the field of IAP.

CRediT authorship contribution statement

Alex Destrieux: Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation, Conceptualization. **Ramavtar Jangra:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Karol Hensel:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zdenko Machala:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Data availability

Data will be made available on request.

References

[1] WHO guidelines for indoor air quality: selected pollutants. https://www.who.int/publications/i/item/9789289002134, 2010. (Accessed 29 May 2025).

[2] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, n.d. www.nature.com/jea.

[3] W.W. Nazaroff, Inhalation intake fraction of pollutants from episodic indoor emissions, Build. Environ. 43 (2008) 269–277, https://doi.org/10.1016/j.buildenv.2006.03.021.

[4] A. Cincinelli, T. Martellini, Indoor air quality and health, Int. J. Environ. Res. Publ. Health 14 (2017) 1286, https://doi.org/10.3390/ijerph14111286.

[5] M. Mannan, S.G. Al-Ghamdi, Indoor air quality in buildings: a comprehensive review on the factors influencing air pollution in residential and commercial structure, Int. J. Environ. Res. Publ. Health 18 (2021) 3276, https://doi.org/10.3390/ijerph18063276.

[6] D.Y.C. Leung, Outdoor-indoor air pollution in urban environment: challenges and opportunity, Front. Environ. Sci. 2 (2015), https://doi.org/10.3389/fenvs.2014.00069.

[7] S. Raju, T. Siddharthan, M.C. McCormack, Indoor air pollution and respiratory health, Clin. Chest Med. 41 (2020) 825–843, https://doi.org/10.1016/j.ccm.2020.08.014.

[8] P. Kumar, A.B. Singh, T. Arora, S. Singh, R. Singh, Critical review on emerging health effects associated with the indoor air quality and its sustainable management, Sci. Total Environ. 872 (2023) 162163, https://doi.org/10.1016/j.scitotenv.2023.162163.

[9] A.A. Mansor, S. Abdullah, A.N. Ahmad, A.N. Ahmed, M.F.R. Zulkifli, S.M. Jusoh, M. Ismail, Indoor air quality and sick building syndrome symptoms in administrative office at public university, Dialog. Health 4 (2024) 100178, https://doi.org/10.1016/j.dialog.2024.100178.

[10] S. Gawande, R. Tiwari, P. Narayanan, A. Bhadri, Indoor air quality and sick building syndrome: are green buildings better than conventional buildings? Indian J. Occup. Environ. Med. 24 (2020) 30, https://doi.org/10.4103/ijoem.IJOEM_148_19.

[11] WHO guidelines for indoor air quality: household fuel combustion. https://www.who.int/publications/i/item/9789241548885, 2014. (Accessed 29 May 2025).

[12] G. Suleyman, G. Alangaden, A.C. Bardossy, The role of environmental contamination in the transmission of nosocomial pathogens and healthcare-associated infections, Curr. Infect. Dis. Rep. 20 (2018) 12, https://doi.org/10.1007/s11908-018-0620-2.

[13] I. Eames, J.W. Tang, Y. Li, P. Wilson, Airborne transmission of disease in hospitals, J. R. Soc. Interface 6 (2009), https://doi.org/10.1098/rsif.2009.0407.focus.

[14] K. Apte, S. Salvi, Household air pollution and its effects on health, F1000Res 5 (2016) 2593, https://doi.org/10.12688/f1000research.7552.1.

[15] P. Srikanth, S. Sudharsanam, R. Steinberg, Bio-aerosols in indoor environment: composition, health effects and analysis, Indian J. Med. Microbiol. 26 (2008) 302, https://doi.org/10.4103/0255-0857.43555.

[16] I. Chirca, The hospital environment and its microbial burden: challenges and solutions, Future Microbiol. 14 (2019) 1007–1010, https://doi.org/10.2217/fmb-2019-0140.

[17] L. Bonadonna, R. Briancesco, A.M. Coccia, Analysis of microorganisms in hospital environments and potential risks, 53–62, https://doi.org/10.1007/978-3-319-49160-8_5, 2017.

[18] K.-H. Kim, E. Kabir, S.A. Jahan, Airborne bioaerosols and their impact on human health, J. Environ. Sci. 67 (2018) 23–35, https://doi.org/10.1016/j.jes.2017.08.027.

[19] L. Song, J. Zhou, C. Wang, G. Meng, Y. Li, M. Jarin, Z. Wu, X. Xie, Airborne pathogenic microorganisms and air cleaning technology development: a review, J. Hazard Mater. 424 (2022) 127429, https://doi.org/10.1016/j.jhazmat.2021.127429.

[20] W.A. Rutala, D.J. Weber, Disinfection, sterilization, and control of hospital waste, in: Mandell, Douglas, and Bennett's Principles and Practice of Infectious Diseases, Elsevier, 2015, pp. 3294–3309.e4, https://doi.org/10.1016/B978-1-4557-4801-3.00301-5.

[21] V. Kasi, N. Elango, S. Ananth, B. Vembhu, J. Poornima, Occupational exposure to photocopiers and their toners cause genotoxicity, Hum. Exp. Toxicol. 37 (2018) 205–217, https://doi.org/10.1177/0960327117693068.

[22] E. Gallego, X. Roca, J.F. Perales, X. Guardino, Determining indoor air quality and identifying the origin of odour episodes in indoor environments, J. Environ. Sci. 21 (2009) 333–339, https://doi.org/10.1016/S1001-0742(08)62273-1.

[23] Y.F. Xing, Y.H. Xu, M.H. Shi, Y.X. Lian, The impact of PM2.5 on the human respiratory system, J. Thorac. Dis. 8 (2016) E69–E74, https://doi.org/10.3978/j.issn.2072-1439.2016.01.19.

[24] WHO global air quality guidelines. https://www.who.int/publications/i/item/9789240034228, 2021. (Accessed 29 May 2025).

[25] D. Kajjoba, H. Kasedde, J.B. Kirabira, R. Wesonga, R. Mugwanya, J.D. Lwanyaga, P.W. Olupot, Impact of natural ventilation and outdoor environment on indoor air quality and occupant health in low-income tropical housing, Energy Rep. 12 (2024) 4184–4194, https://doi.org/10.1016/j.egyr.2024.10.004.

[26] A. Luengas, A. Barona, C. Hort, G. Gallastegui, V. Platel, A. Elias, A review of indoor air treatment technologies, Rev. Environ. Sci. Biotechnol. 14 (2015) 499–522, https://doi.org/10.1007/s11157-015-9363-9.

[27] D. Le Pham, K.-M. Le, D.D.K. Truong, H.T.T. Le, T.H.K. Trinh, Environmental allergen reduction in asthma management: an overview, Front. Allerg. 4 (2023), https://doi.org/10.3389/falgy.2023.1229238.

[28] V. Van Tran, D. Park, Y.-C. Lee, Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality, Int. J. Environ. Res. Publ. Health 17 (2020) 2927, https://doi.org/10.3390/ijerph17082927.

[29] W.J. Fisk, Q. Lei-Gomez, M.J. Mendell, Meta-analyses of the associations of respiratory health effects with dampness and mold in homes, Indoor Air 17 (2007) 284–296, https://doi.org/10.1111/j.1600-0668.2007.00475.x.

[30] S.K. Das, Harmful health effects of cigarette smoking, Mol. Cell. Biochem. 253 (2003) 159–165, https://doi.org/10.1023/A:1026024829294.

[31] J. (Jim) Zhang, K.R. Smith, Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions, Environ. Health Perspect. 115 (2007) 848–855, https://doi.org/10.1289/ehp.9479.

[32] K.-S. Liu, M.K. Paz, P. Flessel, J. Waldman, J. Girman, Unintentional carbon monoxide deaths in California from residential and other nonvehicular sources, archives of environmental health, Int. J. 55 (2000) 375–381, https://doi.org/10.1080/00039890009604033.

[33] D.A. Sarigiannis, S.P. Karakitsios, A. Gotti, I.L. Liakos, A. Katsoyiannis, Exposure to major volatile organic compounds and carbonyls in European indoor environments and associated health risk, Environ. Int. 37 (2011) 743–765, https://doi.org/10.1016/j.envint.2011.01.005.

[34] J. (Jim) Zhang, Y. Wei, Z. Fang, Ozone pollution: a major health hazard worldwide, Front. Immunol. 10 (2019), https://doi.org/10.3389/fimmu.2019.02518.

[35] D.E. Schraufnagel, The health effects of ultrafine particles, Exp. Mol. Med. 52 (2020) 311–317, https://doi.org/10.1038/s12276-020-0403-3.

[36] A. Afshari, L. Ekberg, L. Forejt, J. Mo, S. Rahimi, J. Siegel, W. Chen, P. Wargocki, S. Zurami, J. Zhang, Electrostatic precipitators as an indoor air cleaner—a literature review, Sustainability 12 (2020) 8774, https://doi.org/10.3390/su12218774.

[37] M.D. Durham, K.E. Baldrey, Flue gas conditioning for improved particle collection in electrostatic precipitators. https://doi.org/10.2172/10143836, 1994.

[38] P. Zhang, Y. Yao, Y. Li, S. Yuan, L. Qi, Influence of NO2 and SO2 on the specific resistance of dust in flue gas, Environ. Sci. Pollut. Control Ser. 26 (2019) 19220–19227, https://doi.org/10.1007/s11356-019-05197-9.

[39] C. Zheng, Z. Shen, Q. Chang, Q. Su, X. Zhu, X. Gao, Experimental study on electrostatic precipitation of low-resistivity high-carbon fly ash at high temperature, Energy Fuels 31 (2017) 6266–6273, https://doi.org/10.1021/acs.energyfuels.7b00107.

[40] A. Jaworek, A. Marchewicz, A.T. Sobczyk, A. Krupa, T. Czech, Two-stage electrostatic precipitator with co- and counter-flow particle prechargers, J. Electrost. 87 (2017) 180–194, https://doi.org/10.1016/j.elstat.2017.04.012.

[41] E. Sokolovskij, A. Kilikevičius, A. Chlebnikovas, J. Matijošius, D. Vainorius, Innovative electrostatic precipitator solutions for efficient removal of fine particulate matter: enhancing performance and energy efficiency, Machines 12 (2024) 761, https://doi.org/10.3390/machines12110761.

[42] S. Dubey, H. Rohra, A. Taneja, Assessing effectiveness of air purifiers (HEPA) for controlling indoor particulate pollution, Heliyon 7 (2021) e07976, https://doi.org/10.1016/j.heliyon.2021.e07976.

[43] P. Zhao, J.A. Siegel, R.L. Corsi, Ozone removal by HVAC filters, Atmos. Environ. 41 (2007) 3151–3160, https://doi.org/10.1016/j.atmosenv.2006.06.059.

[44] K. Li, G. Feng, T. Chen, H. Zhao, Research of electret air filter: a review, Polym. Adv. Technol. 35 (2024), https://doi.org/10.1002/pat.6454.

[45] J.-H. Lin, Y.-H. Shih, C.-H. Huang, M.-F. Lai, S.-A. Lee, B.-C. Shiu, C.-W. Lou, Evaluations of electrostatic filtration efficiency and antibacterial efficacy of antibacterial electret polypropylene filters: effects of using low molecular antibacterial agent as additive, Polymers (Basel) 13 (2021) 3303, https://doi.org/10.3390/polym13193303.

[46] C.A. Grande, Modelling of adsorption technologies for controlling indoor air quality, Adsorption 28 (2022) 1–13, https://doi.org/10.1007/s10450-022-00354-y.

[47] L. Pei, J. Zhou, L. Zhang, Preparation and properties of Ag-coated activated carbon nanocomposites for indoor air quality control, Build. Environ. 63 (2013) 108–113, https://doi.org/10.1016/j.buildenv.2013.02.010.

[48] C. Qian, Air ionizers case study, J. Phys. Conf. Ser. 2029 (2021) 012026, https://doi.org/10.1088/1742-6596/2029/1/012026.

[49] J.-S. Park, B.-J. Sung, K.-S. Yoon, C.-S. Jeong, The bactericidal effect of an ionizer under low concentration of ozone, BMC Microbiol. 16 (2016) 173, https://doi.org/10.1186/s12866-016-0785-5.

[50] K.-H. Kim, J.E. Szulejko, P. Kumar, E.E. Kwon, A.A. Adelodun, P.A.K. Reddy, Air ionization as a control technology for off-gas emissions of volatile organic compounds, Environ. Pollut. 225 (2017) 729–743, https://doi.org/10.1016/j.envpol.2017.03.026.

[51] L. Tymczyna, A. Chmielowiec-Korzeniowska, A. Drabik, The effectiveness of various biofiltration substrates in removing bacteria, endotoxins, and dust from ventilation system exhaust from a chicken hatchery, Poult. Sci. 86 (2007) 2095–2100, https://doi.org/10.1093/ps/86.10.2095.

[52] B. Guieysse, C. Hort, V. Platel, R. Munoz, M. Ondarts, S. Revah, Biological treatment of indoor air for VOC removal: potential and challenges, Biotechnol. Adv. 26 (2008) 398–410, https://doi.org/10.1016/j.biotechadv.2008.03.005.

[53] G. Soreanu, Biotechnologies for improving indoor air quality, in: Start-Up Creation, Elsevier, 2016, pp. 301–328, https://doi.org/10.1016/B978-0-08-100546-0.00012-1.

[54] S. Bandehali, T. Miri, H. Onyeaka, P. Kumar, Current state of indoor air phytoremediation using potted plants and green walls, Atmosphere (Basel) 12 (2021) 473, https://doi.org/10.3390/atmos12040473.

[55] R. Kumar, V. Verma, M. Thakur, G. Singh, B. Bhargava, A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach, Air Qual. Atmos. Health 16 (2023) 1501–1527, https://doi.org/10.1007/s11869-023-01326-z.

[56] K.J. Kim, M. Khalekuzzaman, C.C. Shagol, J.N. Suh, H.J. Kim, Volatile organic compound removal efficiency of green and variegated foliage plants grown under different light intensities, J. Korea Soc. Plants People Environment 20 (2017) 531–542, https://doi.org/10.11628/ksppe.2017.20.5.531.

[57] B.M. da Costa Filho, G.V. Silva, R.A.R. Boaventura, M.M. Dias, J.C.B. Lopes, V.J. P. Vilar, Ozonation and ozone-enhanced photocatalysis for VOC removal from air streams: process optimization, synergy and mechanism assessment, Sci. Total Environ. 687 (2019) 1357–1368, https://doi.org/10.1016/j.scitotenv.2019.05.365.

[58] B. Bayarri, A. Cruz-Alcalde, N. López-Vinent, M.M. Micó, C. Sans, Can ozone inactivate SARS-CoV-2? A review of mechanisms and performance on viruses, J. Hazard Mater. 415 (2021) 125658, https://doi.org/10.1016/j.jhazmat.2021.125658.

[59] N.G. Reed, The history of ultraviolet germicidal irradiation for air disinfection, Publ. Health Rep. 125 (2010) 15–27, https://doi.org/10.1177/003335491012500105.

[60] T.D. Cutler, J.J. Zimmerman, Ultraviolet irradiation and the mechanisms underlying its inactivation of infectious agents, Anim. Health Res. Rev. 12 (2011) 15–23, https://doi.org/10.1017/S1466252311000016.

[61] S. Sankurantripati, F. Duchaine, Indoor air quality control for airborne diseases: a review on portable UV air purifiers, Fluids 9 (2024) 281, https://doi.org/10.3390/fluids9120281.

[62] F. Graeffe, Y. Luo, Y. Guo, M. Ehn, Unwanted indoor air quality effects from using ultraviolet C lamps for disinfection, Environ. Sci. Technol. Lett. 10 (2023) 172–178, https://doi.org/10.1021/acs.estlett.2c00807.

[63] K. Ahlawat, R. Jangra, A. Ish, A. Dixit, D. Fulwani, N. Jain, R. Prakash, Analysis of a UV photocatalytic oxidation-based disinfection system for hydroxyl radicals, negative air ions generation and their impact on inactivation of pathogenic micro-organisms, Rev. Sci. Instrum. 94 (2023), https://doi.org/10.1063/5.0151619.

[64] Y.-W. Li, W.-L. Ma, Photocatalytic oxidation technology for indoor air pollutants elimination: a review, Chemosphere 280 (2021) 130667, https://doi.org/10.1016/j.chemosphere.2021.130667.
[65] Z. Zhou, B. Li, X. Liu, Z. Li, S. Zhu, Y. Liang, Z. Cui, S. Wu, Recent progress in photocatalytic antibacterial, ACS Appl. Bio Mater. 4 (2021) 3909–3936, https://doi.org/10.1021/acsabm.0c01335.
[66] D. Chen, Y. Cheng, N. Zhou, P. Chen, Y. Wang, K. Li, S. Huo, P. Cheng, P. Peng, R. Zhang, L. Wang, H. Liu, Y. Liu, R. Ruan, Photocatalytic degradation of organic pollutants using TiO2-based photocatalysts: a review, J. Clean. Prod. 268 (2020) 121725, https://doi.org/10.1016/j.jclepro.2020.121725.
[67] D. Vildozo, R. Portela, C. Ferronato, J.-M. Chovelon, Photocatalytic oxidation of 2-propanol/toluene binary mixtures at indoor air concentration levels, Appl. Catal., B 107 (2011) 347–354, https://doi.org/10.1016/j.apcatb.2011.07.035.
[68] T. Daikoku, M. Takemoto, Y. Yoshida, T. Okuda, Y. Takahashi, K. Ota, F. Tokuoka, A.T. Kawaguchi, K. Shiraki, Decomposition of organic chemicals in the air and inactivation of aerosol-associated influenza infectivity by photocatalysis, Aerosol Air Qual. Res. 15 (2015) 1469–1484, https://doi.org/10.4209/aaqr.2014.10.0256.
[69] G. Masresha, S.A. Jabasingh, S. Kebede, D. Doo-Arhin, M. Assefa, A review of prospects and challenges of photocatalytic decomposition of volatile organic compounds VOCs under humid environment, Can. J. Chem. Eng. 101 (2023) 6905–6918, https://doi.org/10.1002/cjce.24978.
[70] Y. Zhang, Y. Wang, R. Xie, H. Huang, M.K.H. Leung, J. Li, D.Y.C. Leung, Photocatalytic oxidation for volatile organic compounds elimination: from fundamental research to practical applications, Environ. Sci. Technol. 56 (2022) 16582–16601, https://doi.org/10.1021/acs.est.2c05444.
[71] R. Jangra, K. Ahlawat, A. Dixit, R. Prakash, Efficient deactivation of aerosolized pathogens using a dielectric barrier discharge based cold-plasma detergent in environment device for good indoor air quality, Sci. Rep. 13 (2023) 10295, https://doi.org/10.1038/s41598-023-37014-2.
[72] T. Xia, A. Kleinheksel, E.M. Lee, Z. Qiao, K.R. Wigginton, H.L. Clack, Inactivation of airborne viruses using a packed bed non-thermal plasma reactor, J. Phys. D Appl. Phys. 52 (2019) 255201, https://doi.org/10.1088/1361-6463/ab1466.
[73] P.J. Asilevi, P. Boakye, S. Oduro-Kwarteng, B. Fei-Baffoe, Y.A. Sokama-Neuyam, Indoor air quality improvement and purification by atmospheric pressure Non-Thermal Plasma (NTP), Sci. Rep. 11 (2021) 22830, https://doi.org/10.1038/s41598-021-02276-1.
[74] H.T. Quoc An, T. Pham Huu, T. Le Van, J.M. Cormier, A. Khacef, Application of atmospheric non thermal plasma-catalysis hybrid system for air pollution control: toluene removal, Catal. Today 176 (2011) 474–477, https://doi.org/10.1016/j.cattod.2010.10.005.
[75] A. Mizuno, S. Member, Y. Kisanuki, M. Noguchi, S. Katsura, S. Hwa Lee, Y. Ki Hong, S. Yeon Shin, J. Hoon Kang, Indoor Air Cleaning Using a Pulsed Discharge Plasma, 1998.
[76] J.O. Chae, V. Demidiouk, M. Yeulash, I.C. Choi, T.G. Jung, Experimental study for indoor air control by plasma-catalyst hybrid system, IEEE Trans. Plasma Sci. 32 (2004) 493–497, https://doi.org/10.1109/TPS.2004.826030.
[77] F. Prehn, E. Timmermann, M. Kettlitz, K. Schaufler, S. Günther, V. Hahn, Inactivation of airborne bacteria by plasma treatment and ionic wind for indoor air cleaning, Plasma Process. Polym. 17 (2020), https://doi.org/10.1002/ppap.202000027.
[78] D.A. Aytekin, N. Tetik, Ü.A. Şahin, C. Ayvaz, E. Nurtop, C. Vatansever, F. Can, Needle point bipolar ionization: environmental safety and inactivation of airborne bacteria and corona virus, Environ. Sci. Pollut. Control Ser. 32 (2025) 12360–12371, https://doi.org/10.1007/s11356-025-36441-0.
[79] V.P. Barber, M.B. Goss, L.J. Franco Deloya, L.N. LeMar, Y. Li, E. Helstrom, M. Canagaratna, F.N. Keutsch, J.H. Kroll, Indoor air quality implications of germicidal 222 nm light, Environ. Sci. Technol. 57 (2023) 15990–15998, https://doi.org/10.1021/acs.est.3c05680.
[80] S. Mumtaz, R. Khan, J.N. Rana, R. Javed, M. Iqbal, E.H. Choi, I. Han, Review on the biomedical and environmental applications of nonthermal plasma, Catalysts 13 (2023) 685, https://doi.org/10.3390/catal13040685.
[81] S. Das, V.P. Gajula, S. Mohapatra, G. Singh, S. Kar, Role of cold atmospheric plasma in microbial inactivation and the factors affecting its efficacy, Health Sci. Rev. 4 (2022) 100037, https://doi.org/10.1016/j.hsr.2022.100037.
[82] X. Liao, D. Liu, Q. Xiang, J. Ahn, S. Chen, X. Ye, T. Ding, Inactivation mechanisms of non-thermal plasma on microbes: a review, Food Control 75 (2017) 83–91, https://doi.org/10.1016/j.foodcont.2016.12.021.
[83] W.A. Rutala, D.J. Weber, Disinfection and sterilization in health care facilities, Infect. Dis. Clin. 30 (2016) 609–637, https://doi.org/10.1016/j.idc.2016.04.002.
[84] S.H. Ki, K. Masur, K.Y. Baik, E.H. Choi, Effects of humidity on room disinfection by dielectric barrier discharge plasma, J. Phys. D Appl. Phys. 52 (2019) 425204, https://doi.org/10.1088/1361-6463/ab3066.
[85] R. Jangra, K. Ahlawat, M.K. Mohan, R. Prakash, Indoor air disinfection by non thermal atmospheric pressure plasma: a comparative study of performance in low and high humidity environments, Phys Scr 99 (2024) 085612, https://doi.org/10.1088/1402-4896/ad6353.
[86] W. Zhou, Z. Ye, A. Nikiforov, J. Chen, J. Wang, L. Zhao, X. Zhang, The influence of relative humidity on double dielectric barrier discharge plasma for chlorobenzene removal, J. Clean. Prod. 288 (2021) 125502, https://doi.org/10.1016/j.jclepro.2020.125502.
[87] R.S. Islamov, Y.A. Krishtafovich, A peculiarity of silver-based corona wire heating on ozone generation, J. Electrost. 69 (2011) 236–239, https://doi.org/10.1016/j.elstat.2011.03.015.
[88] A. Yehia, A. Mizuno, Suppression of the ozone generation in the positive and negative dc corona discharge, Int J Plasma Environ Sci. Technol. 2 (2008) 44–49.
[89] L. Liu, J. Guo, J. Li, L. Sheng, The effect of wire heating and configuration on ozone emission in a negative ion generator, J. Electrost. 48 (2000) 81–91, https://doi.org/10.1016/S304-3886(99)00049-2.
[90] H.J. Kim, B. Han, Y.J. Kim, T. Oda, H. Won, Submicrometer particle removal indoors by a novel electrostatic precipitator with high clean air delivery rate, low ozone emissions, and carbon fiber ionizer, Indoor Air 23 (2013) 369–378, https://doi.org/10.1111/ina.12037.
[91] Z. Ye, J.M. Giraudon, N. De Geyter, R. Morent, J.F. Lamonier, The design of MnOx based catalyst in post-plasma catalysis configuration for toluene abatement, Catalysts 8 (2018), https://doi.org/10.3390/catal8020091.
[92] X. Tang, F. Feng, L. Ye, X. Zhang, Y. Huang, Z. Liu, K. Yan, Removal of dilute VOCs in air by post-plasma catalysis over Ag-based composite oxide catalysts, Catal. Today 211 (2013) 39–43, https://doi.org/10.1016/j.cattod.2013.04.026.
[93] B. Wang, C. Chi, M. Xu, C. Wang, D. Meng, Plasma-catalytic removal of toluene over CeO2-MnOx catalysts in an atmosphere dielectric barrier discharge, Chem. Eng. J. 322 (2017) 679–692, https://doi.org/10.1016/j.cej.2017.03.153.
[94] E. Krugly, O. Pitak, D. Ciuzas, M. Tichonovas, I. Stasiulaitiene, I. Urniezaite, L. Kliucininkas, D. Martuzevicius, VOC removal from ventilation air by gas-to-particle conversion: towords the Enhancement of process efficiency, Build. Environ. 209 (2022) 108647, https://doi.org/10.1016/j.buildenv.2021.108647.
[95] P. Li, J.A. Koziel, N. Macedo, J.J. Zimmerman, D. Wrzesinski, E. Sobotka, M. Balderas, W.B. Walz, R.V. Paris, M. Lee, D. Liu, B. Yedilbayev, B.C. Ramirez, W.S. Jenks, Evaluation of an air cleaning device equipped with filtration and UV: comparison of removal efficiency on particulate matter and viable airborne bacteria in the inlet and treated air, Int. J. Environ. Res. Publ. Health 19 (2022) 16135, https://doi.org/10.3390/ijerph192316135.
[96] S. Srivastava, X. Zhao, A. Manay, Q. Chen, Effective ventilation and air disinfection system for reducing coronavirus disease 2019 (COVID-19) infection risk in office buildings, Sustain. Cities Soc. 75 (2021) 103408, https://doi.org/10.1016/j.scs.2021.103408.
[97] Y.H. Lu, H. Wu, H.H. Zhang, W.S. Li, A.C.K. Lai, Synergistic disinfection of aerosolized bacteria and bacteriophage by far-UVC (222-nm) and negative air ions, J. Hazard Mater. 441 (2023), https://doi.org/10.1016/j.jhazmat.2022.129876.
[98] K.M. Ratliff, L. Oudejans, J. Archer, W. Calfee, J.U. Gilberry, D.A. Hook, W. E. Schoppman, R.W. Yaga, L. Brooks, S. Ryan, Large-scale evaluation of microorganism inactivation by bipolar ionization and photocatalytic devices, Build. Environ. 227 (2023) 109804, https://doi.org/10.1016/j.buildenv.2022.109804.
[99] Air Purifier Market Size & Trends, n.d. https://www.grandviewresearch.com/industry-analysis/filters-market.
[100] https://www.daikin-streamer.com/en/result/.
[101] https://www.wellairsolutions.com/bpi-research.
[102] https://global.sharp/pci/en/certified/.
[103] J. Saffell, S. Nehr, Improving indoor air quality through standardization, Standards 3 (2023) 240–267, https://doi.org/10.3390/standards3030019.
[104] A. Ibhadon, P. Fitzpatrick, Heterogeneous photocatalysis: recent advances and applications, Catalysts 3 (2013) 189–218, https://doi.org/10.3390/catal3010189.
[105] D. Mei, X. Zhu, C. Wu, B. Ashford, P.T. Williams, X. Tu, Plasma-photocatalytic conversion of CO 2 at low temperatures: understanding the synergistic effect of plasma-catalysis, Appl. Catal., B 182 (2016) 525–532, https://doi.org/10.1016/j.apcatb.2015.09.052.
[106] T. Nozaki, X. Chen, D.-Y. Kim, C. Zhan, Combination of DBD and catalysts for CH4 and CO2 conversion: basics and applications, Plasma Chem. Plasma Process. 43 (2023) 1385–1410, https://doi.org/10.1007/s11090-023-10382-3.
[107] M. Laroussi, F. Leipold, Evaluation of the roles of reactive species, heat, and UV radiation in the inactivation of bacterial cells by air plasmas at atmospheric pressure, Int. J. Mass Spectrom. 233 (2004) 81–86, https://doi.org/10.1016/j.ijms.2003.11.016.
[108] H.H. Kim, Y. Teramoto, N. Negishi, A. Ogata, A multidisciplinary approach to understand the interactions of nonthermal plasma and catalyst: a review, Catal. Today 256 (2015) 13–22, https://doi.org/10.1016/j.cattod.2015.04.009.
[109] T. Sano, N. Negishi, E. Sakai, S. Matsuzawa, Contributions of photocatalytic/catalytic activities of TiO2 and γ-Al2O3 in nonthermal plasma on oxidation of acetaldehyde and CO, J. Mol. Catal. Chem. 245 (2006) 235–241, https://doi.org/10.1016/j.molcata.2005.10.002.
[110] Y. Nosaka, A.Y. Nosaka, Generation and detection of reactive oxygen species in photocatalysis, Chem. Rev. 117 (2017) 11302–11336, https://doi.org/10.1021/acs.chemrev.7b00161.
[111] Y. Murakami, E. Kenji, A.Y. Nosaka, Y. Nosaka, Direct detection of OH radicals diffused to the gas phase from the UV-irradiated photocatalytic TiO2 surfaces by means of laser-induced fluorescence spectroscopy, J. Phys. Chem. B 110 (2006) 16808–16811, https://doi.org/10.1021/jp063293c.
[112] M. Qu, Z. Cheng, Z. Sun, D. Chen, J. Yu, J. Chen, Non-thermal plasma coupled with catalysis for VOCs abatement: a review, Process Saf. Environ. Prot. 153 (2021) 139–158, https://doi.org/10.1016/j.psep.2021.06.028.
[113] L. Liu, G. Shao, C. Ma, A. Nikiforov, N. De Geyter, R. Morent, Plasma-catalysis for VOCs decomposition: a review on micro- and macroscopic modeling, J. Hazard Mater. 451 (2023) 131100, https://doi.org/10.1016/j.jhazmat.2023.131100.
[114] J. Zhou, T. Wei, X. An, Combining non-thermal plasma technology with photocatalysis: a critical review, Phys. Chem. Chem. Phys. 25 (2023) 1538–1545, https://doi.org/10.1039/D2CP04836A.
[115] B. Loenders, R. Michiels, A. Bogaerts, Is a catalyst always beneficial in plasma catalysis? Insights from the many physical and chemical interactions, J. Energy Chem. 85 (2023) 501–533, https://doi.org/10.1016/j.jechem.2023.06.016.

[116] L. Pinard, C. Batiot-Dupeyrat, Non-thermal plasma for catalyst regeneration: a review, Catal. Today 426 (2024) 114372, https://doi.org/10.1016/j.cattod.2023.114372.

[117] Z. Cui, C. Zhou, A. Jafarzadeh, X. Zhang, Y. Hao, L. Li, A. Bogaerts, SF6 degradation in a γ-Al2O3 packed DBD system: effects of hydration, reactive gases and plasma-induced surface charges, Plasma Chem. Plasma Process. 43 (2023) 635–656, https://doi.org/10.1007/s11090-023-10320-3.

[118] K. Fu, Y. Su, Y. Zheng, R. Han, Q. Liu, Novel monolithic catalysts for VOCs removal: a review on preparation, carrier and energy supply, Chemosphere 308 (2022) 136256, https://doi.org/10.1016/j.chemosphere.2022.136256.

[119] H.H. Kim, A.A. Abdelaziz, Y. Teramoto, T. Nozaki, K. Hensel, Y.S. Mok, S. Saud, D.B. Nguyen, D.H. Lee, W.S. Kang, Interim report of plasma catalysis: footprints in the past and blueprints for the future, Int. J. Plasma Environ. Sci. Technol. 15 (2021), https://doi.org/10.34343/ijpest.2021.15.e01004.

[120] K. Hensel, Microdischarges in ceramic foams and honeycombs, The European Physical Journal D 54 (2009) 141–148, https://doi.org/10.1140/epjd/e2009-00073-1.

[121] K. Hensel, V. Martišovitš, Z. Machala, M. Janda, M. Leštinský, P. Tardiveau, A. Mizuno, Electrical and optical properties of AC microdischarges in porous ceramics, Plasma Process. Polym. 4 (2007) 682–693, https://doi.org/10.1002/ppap.200700022.

[122] R. Cimerman, M. Cíbiková, L. Satrapinskyy, K. Hensel, The effect of packing material properties on tars removal by plasma catalysis, Catalysts 10 (2020) 1476, https://doi.org/10.3390/catal10121476.

[123] C. Qin, H. Guo, P. Liu, W. Bai, J. Huang, X. Huang, X. Dang, D. Yan, Toluene abatement through adsorption and plasma oxidation using ZSM-5 mixed with γ-Al2O3, TiO2 or BaTiO3, J. Ind. Eng. Chem. 63 (2018) 449–455, https://doi.org/10.1016/j.jiec.2018.03.005.

[124] H.H. Kim, Y. Teramoto, A. Ogata, Time-resolved imaging of positive pulsed corona-induced surface streamers on TiO2 and γ-Al2O3-supported Ag catalysts, J. Phys. Appl. Phys. 49 (415204) (2016), https://doi.org/10.1088/0022-3727/49/45/459501. J Phys D Appl Phys 49 (2016).

[125] H.H. Kim, J.H. Kim, A. Ogata, Microscopic observation of discharge plasma on the surface of zeolites supported metal nanoparticles, J. Phys. D Appl. Phys. 42 (2009), https://doi.org/10.1088/0022-3727/42/13/135210.

[126] W. Wang, H.H. Kim, K. Van Laer, A. Bogaerts, Streamer propagation in a packed bed plasma reactor for plasma catalysis applications, Chem. Eng. J. 334 (2018) 2467–2479, https://doi.org/10.1016/j.cej.2017.11.139.

[127] M. Monir Hossain, M. Robayet Ahasan, R. Wang, Influence of catalyst shape on plasma-assisted dry reforming of methane: a comparative study of Ni-CeO2 nanocubes and nano-octahedra, Chem. Eng. J. 496 (2024) 154193, https://doi.org/10.1016/j.cej.2024.154193.

[128] X. Feng, H. Liu, C. He, Z. Shen, T. Wang, Synergistic effects and mechanism of a non-thermal plasma catalysis system in volatile organic compound removal: a review, Catal. Sci. Technol. 8 (2018) 936–954, https://doi.org/10.1039/C7CY01934C.

[129] E.C. Neyts, A. Bogaerts, Understanding plasma catalysis through modelling and simulation—a review, J. Phys. D Appl. Phys. 47 (2014) 224010, https://doi.org/10.1088/0022-3727/47/22/224010.

[130] E.C. Neyts, K. (Ken) Ostrikov, M.K. Sunkara, A. Bogaerts, Plasma catalysis: synergistic effects at the nanoscale, Chem. Rev. 115 (2015) 13408–13446, https://doi.org/10.1021/acs.chemrev.5b00362.

[131] A.A. Assadi, A. Bouzaza, M. Lemasle, D. Wolbert, Acceleration of trimethylamine removal process under synergistic effect of photocatalytic oxidation and surface discharge plasma reactor, Can. J. Chem. Eng. 93 (2015) 1239–1246, https://doi.org/10.1002/cjce.22211.

[132] B. Zhu, L.-Y. Zhang, M. Li, Y. Yan, X.-M. Zhang, Y.-M. Zhu, High-performance of plasma-catalysis hybrid system for toluene removal in air using supported Au nanocatalysts, Chem. Eng. J. 381 (2020) 122599, https://doi.org/10.1016/j.cej.2019.122599.

[133] K.L. Pan, M.B. Chang, Plasma catalytic oxidation of toluene over double perovskite-type oxide via packed-bed DBD, Environ. Sci. Pollut. Control Ser. 26 (2019) 12948–12962, https://doi.org/10.1007/s11356-019-04714-0.

[134] W. Abou Saoud, A.A. Assadi, M. Guiza, A. Bouzaza, W. Aboussaoud, I. Soutrel, A. Ouederni, D. Wolbert, S. Rtimi, Abatement of ammonia and butyraldehyde under non-thermal plasma and photocatalysis: oxidation processes for the removal of mixture pollutants at pilot scale, Chem. Eng. J. 344 (2018) 165–172, https://doi.org/10.1016/j.cej.2018.03.068.

[135] T. Zadi, M. Azizi, N. Nasrallah, A. Bouzaza, R. Maachi, D. Wolbert, S. Rtimi, A. A. Assadi, Indoor air treatment of refrigerated food chambers with synergetic association between cold plasma and photocatalysis: process performance and photocatalytic poisoning, Chem. Eng. J. 382 (2020) 122951, https://doi.org/10.1016/j.cej.2019.122951.

[136] A. Bogaerts, X. Tu, J.C. Whitehead, G. Centi, L. Lefferts, O. Guaitella, F. Azzolina-Jury, H.-H. Kim, A.B. Murphy, W.F. Schneider, T. Nozaki, J.C. Hicks, A. Rousseau, F. Thevenet, A. Khacef, M. Carreon, The 2020 plasma catalysis roadmap, J. Phys. D Appl. Phys. 53 (2020) 443001, https://doi.org/10.1088/1361-6463/ab9048.

[137] A.C.K. Lai, A.C.T. Cheung, M.M.L. Wong, W.S. Li, Evaluation of cold plasma inactivation efficacy against different airborne bacteria in ventilation duct flow, Build. Environ. 98 (2016) 39–46, https://doi.org/10.1016/j.buildenv.2015.12.005.

[138] A.J.M. Pemen, V.R. Chirumamilla, F.J.C.M. Beckers, W.F.L.M. Hoeben, T. Huiskamp, An SDBD plasma-catalytic system for on-demand air purification, IEEE Trans. Plasma Sci. 46 (2018) 4078–4090, https://doi.org/10.1109/TPS.2018.2855402.

[139] D. Hernández-Díaz, D. Martos-Ferreira, V. Hernández-Abad, R. Villar-Ribera, Q. Tarrés, J.I. Rojas-Sola, Indoor PM2.5 removal efficiency of two different non-thermal plasma systems, J. Environ. Manag. 278 (2021) 111515, https://doi.org/10.1016/j.jenvman.2020.111515.

[140] R. Jangra, K. Ahlawat, R. Prakash, Investigating the role of active air ions and hydroxyl radicals on the eradication of ESKAPE bacteria using non-equilibrium atmospheric air cold plasma, IEEE Trans. Radiat. Plasma Med. Sci. 9 (2025) 515–527, https://doi.org/10.1109/TRPMS.2024.3454542.

[141] R. Jangra, K. Ahlawat, R. Prakash, An SDBD plasma-based source for efficient degradation of VOCs in an enclosed environment, Phys. Lett. 490 (2023) 129184, https://doi.org/10.1016/j.physleta.2023.129184.

[142] M. Tański, A. Berendt, J. Mizeraczyk, Closed SDBD-driven two-stage electrostatic precipitator, J. Clean. Prod. 226 (2019) 74–84, https://doi.org/10.1016/j.jclepro.2019.03.280.

[143] J. Van Durme, J. Dewulf, W. Sysmans, C. Leys, H. Van Langenhove, Efficient toluene abatement in indoor air by a plasma catalytic hybrid system, Appl. Catal., B 74 (2007) 161–169, https://doi.org/10.1016/j.apcatb.2007.02.006.

[144] H. Ge, D. Hu, X. Li, Y. Tian, Z. Chen, Y. Zhu, Removal of low-concentration benzene in indoor air with plasma-MnO 2 catalysis system, J. Electrost. 76 (2015) 216–221, https://doi.org/10.1016/j.elstat.2015.06.003.

[145] Y. Zeng, R. Xie, J. Cao, Z. Chen, Q. Fan, B. Liu, X. Lian, H. Huang, Simultaneous removal of multiple indoor-air pollutants using a combined process of electrostatic precipitation and catalytic decomposition, Chem. Eng. J. 388 (2020) 124219, https://doi.org/10.1016/j.cej.2020.124219.

[146] T. Vazquez, A. Lavrikova, D. Wiedermann, J. Babic, M. Palko, M. Palko, Z. Machala, Non-thermal plasma coupled with photocatalysis for indoor air treatment: effects on VOCs and bio-aerosols, J. Electrostat. 138, Under Rev. (2025).

[147] P. Mohammadi, F. Ghorbani-Shahna, A. Bahrami, A.A. Rafati, M. Farhadian, Plasma-photocatalytic degradation of gaseous toluene using SrTiO3/rGO as an efficient heterojunction for by-products abatement and synergistic effects, J. Photochem. Photobiol. Chem. 394 (2020) 112460, https://doi.org/10.1016/j.jphotochem.2020.112460.

[148] D. Li, J. Lu, C. Wang, Y. Xing, S. Liang, R. Wang, X. Zhang, Y. Liu, Photo-plasma catalytic degradation of high concentration volatile organic compounds, Appl. Catal. Gen. 647 (2022) 118908, https://doi.org/10.1016/j.apcata.2022.118908.

[149] A.H. Mamaghani, F. Haghighat, C.-S. Lee, Effect of titanium dioxide properties and support material on photocatalytic oxidation of indoor air pollutants, Build. Environ. 189 (2021) 107518, https://doi.org/10.1016/j.buildenv.2020.107518.

[150] H. Whiley, T.P. Keerthirathne, E.J. Kuhn, M.A. Nisar, A. Sibley, P. Speck, K. E. Ross, Efficacy of the PlasmaShield®, a non-thermal, plasma-based air purification device, in removing airborne microorganisms, Electrochem 3 (2022) 276–284, https://doi.org/10.3390/electrochem3020019.