# A STATE-OF-THE-ART REVIEW ON INDOOR AIR POLLUTION AND THE POTENTIAL OF BIOTECHNOLOGIES FOR INDOOR AIR PURIFICATION

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**Abstract**

Indoor air pollution has traditionally received less attention than outdoors pollution despite indoors pollutant levels are typically twice higher, and people spend 80-90 % of their life in increasing air-tight buildings. More than 5 million people die every year prematurely from illnesses attributable to poor indoor air quality, which also causes multi-millionaire losses due to reduced employee's productivity, material damages and increased health system expenses. Indoor air pollutants include particulate matter, biological pollutants and over 400 different chemical organic and inorganic compounds, whose concentrations are governed by several outdoor and indoor factors. Prevention of pollutant is not always technically feasible, so the implementation of cost-effective active abatement units is required. Up to date no single physical-chemical technology is capable of coping with all indoor air pollutants in a cost-

effective manner. This problem requires the use of sequential technology configurations at the expenses of superior capital and operating costs. In addition, the performance of conventional physical-chemical technologies is still limited by the low concentrations, the diversity and the variability of pollutants in indoor environments. In this context, biotechnologies have emerged as a cost-effective and sustainable platform capable of coping with these limitations based on the biocatalytic action of plants, bacteria, fungi and microalgae. Indeed, biological-based purification systems can improve the energy efficiency of buildings, while providing additional aesthetic and psychological benefits. This review critically assessed the state-of-the-art of the indoor air pollution problem and prevention strategies, along with the recent advances in physical-chemical and biological technologies for indoor pollutants abatement.

**Keywords**: air pollutant; biotechnology; indoor air quality; prevention strategy; physical-chemical technology; volatile organic compound.

**Highlights**:

- A state-of-the-art review on the global problem of poor indoor air quality
- Typology, sources and health risks of the most common indoor pollutants are revised
- Measures for prevention and abatement of indoor pollutants are carefully examined
- Evaluation of the performance of traditional physical-chemical methods
- Assessment of innovative and sustainable systems based on biotechnologies

**Abbreviation list**

AC – Activated carbon

BF – Biofilter

BTF – Biotrickling filter

BTEX – Benzene, toluene, ethylbenzene and xylene

CADR - Clean Air Delivery Rate

DMS – Dimethyl sulfide

EBRT – Empty bed residence time

EPA – Environmental Protection Agency

ETS – Environmental tobacco smoke

HCHO – Formaldehyde

HVAC – Heating, Ventilation and Air Conditioning

IAQ – Indoor air quality

IEQ - Indoor Environmental Quality

LCM – Carbon microspheres

LCNT – Carbon nanotubes

MERV – Minimum efficiency reporting value

MOF – Metal oxide framework

NTP – Non-thermal plasma

PAN – Polyacrylonitrile

PBTF – Plant-based biotrickling filter

PBDEs – Polybrominated diphenyl ethers

PCO – Photocatalytic oxidation

PDMS – Polydimethylsiloxane

PE – Polyethylene

PAHs – Polycyclic aromatic hydrocarbons

PM – Particulate matter

PP - Polypropylene

$Ppm_v$ – Volumetric parts-per-million

PU - Polyurethane

PVC – Polyvinylchloride

REACH – Registration, Evaluation and Authorization of Chemicals system

RH – Relative humidity

rGO – Reduced graphene oxide

TPPB – Two-liquid phase partitioning bioreactor

TVOC – Total volatile organic compounds

UV – Ultraviolet radiation

VICs – Volatile inorganic compounds

Vis – Visible radiation

VOCs – Volatile organic compounds

WHO – World Health Organization

ZIF – Zeolitic imidazole framework

## 1. The indoor air quality problem

Air pollution and human exposure to low-quality air is nowadays the most critical environmental threat to public health worldwide according to the World Health Organization (WHO) (World Health Organization, 2016). Recent reports have indicated that, at a global scale, 1 out of 10 deaths are attributable to air pollution. Indeed, air pollution alone caused approximately 5.5 million deaths in 2013 in the world (World Bank and Institute for Health Metrics and Evaluation, 2016). At a European level, recently updated data have ascribed more than 500,000 premature deaths in 2016 to long-term exposure to polluted air, from which 412,000 corresponded to particulate matter (PM), 71,000 to $NO_2$, and 15,000 to $O_3$ (European Environmental Agency, 2019). These effects will be even more critical due to the continuous growth of major cities. Indeed, about 90% of the population worldwide lives in urban areas exposed to air quality levels that exceed the WHO guidelines (World Health Organization, 2016), which are typically based on PM pollution.

The latest studies on human exposure to indoor pollution revealed that indoor environments could be at least twice as polluted as outdoor environments (European Comission, 2003). Indeed, the air in an urban street with average traffic might actually be cleaner than the air in a living room. Traditionally, indoor air pollution has received significantly less attention than outdoor air pollution, especially in highly industrialized or dense traffic areas. However, the threats posed by a long-term exposure to indoor air pollution have become more apparent in recent years (European Environment Agency, 2013) as buildings are progressively sealed against the outside environment to obtain heating and cooling energy cost savings. Many buildings rely entirely on mechanical ventilation to recirculate indoor air with a greatly reduced outdoor air dilution level, leading to the accumulation of indoor pollutants. A recent commission report estimated that nearly 3 billion people worldwide are daily exposed to poor indoor air quality (IAQ) caused by the use of solid fuels for cooking, heating and lighting. This report concluded that household air pollution is a major contributor to global figures for

morbidity and mortality, with major effects on respiratory and cardiovascular systems (Royal College of Physicians, 2016). Additionally, the report highlighted the significant contribution of poor IAQ to the total number of premature deaths. At a global level, the WHO estimated that each year 4.3 million people die prematurely from illnesses attributable to indoor air pollution (World Health Organization, 2014), almost all in low and middle income countries, with pollutants produced by indoor combustion processes, such as cooking or heating, as the main cause of deficient IAQ. Moreover, the prevalence of health problems related with IAQ such as sick building syndrome, building related illness or multiple chemical sensitivity has been extensively reported (Burge, 2004). Although the levels of indoor air pollutants and their associated symptoms may decrease in new or recently renovated buildings during the first half year, poor IAQ and its associated symptoms have been reported over years (INSHT, 2015).

In this context, human exposure to indoor air (houses, workplaces, public buildings or means of transport) exceeds 80 % in developed countries and 85-90 % in Europe (European Comission, 2003) (Figure 1). Likewise, the National Human Activity Pattern Survey in the US revealed that an adult spends 86% of his time indoors, to which a further 6% must be added as time spent inside vehicles or public transport (Marć et al., 2018). There has been a significant global shift in the economy from the manufacturing sector towards the service and knowledge-based sectors, which operate in indoor office environments (Al Horr et al., 2016). Poor IAQ has been classified as a priority problem affecting children's health, while it is considered as one of the largest national environmental threats by the US-EPA (Guieysse et al., 2008).

Besides being responsible for many respiratory illnesses, allergies and even cancerous diseases, poor IAQ has also a noteworthy economic impact since it damages valuable objects from libraries, archives or museums, and may reduce employee's productivity in working places by 10-15 % (Cincinelli et al., 2016) (Figure 1). The costs associated to air pollution in the WHO European Region, including exposure to both outdoor and indoor air, amounted to 1.431$ trillions in 2010, from which 42.9$ billion corresponded to Spain (WHO Regional Office for

141 Europe, 2015). If only IAQ is considered (in terms of mortality, loss of productivity, and
142 illnesses and sick leaves), recent studies have calculated annual expenses of up to 20,000
143 million € in France (ANSES et al., 2014).

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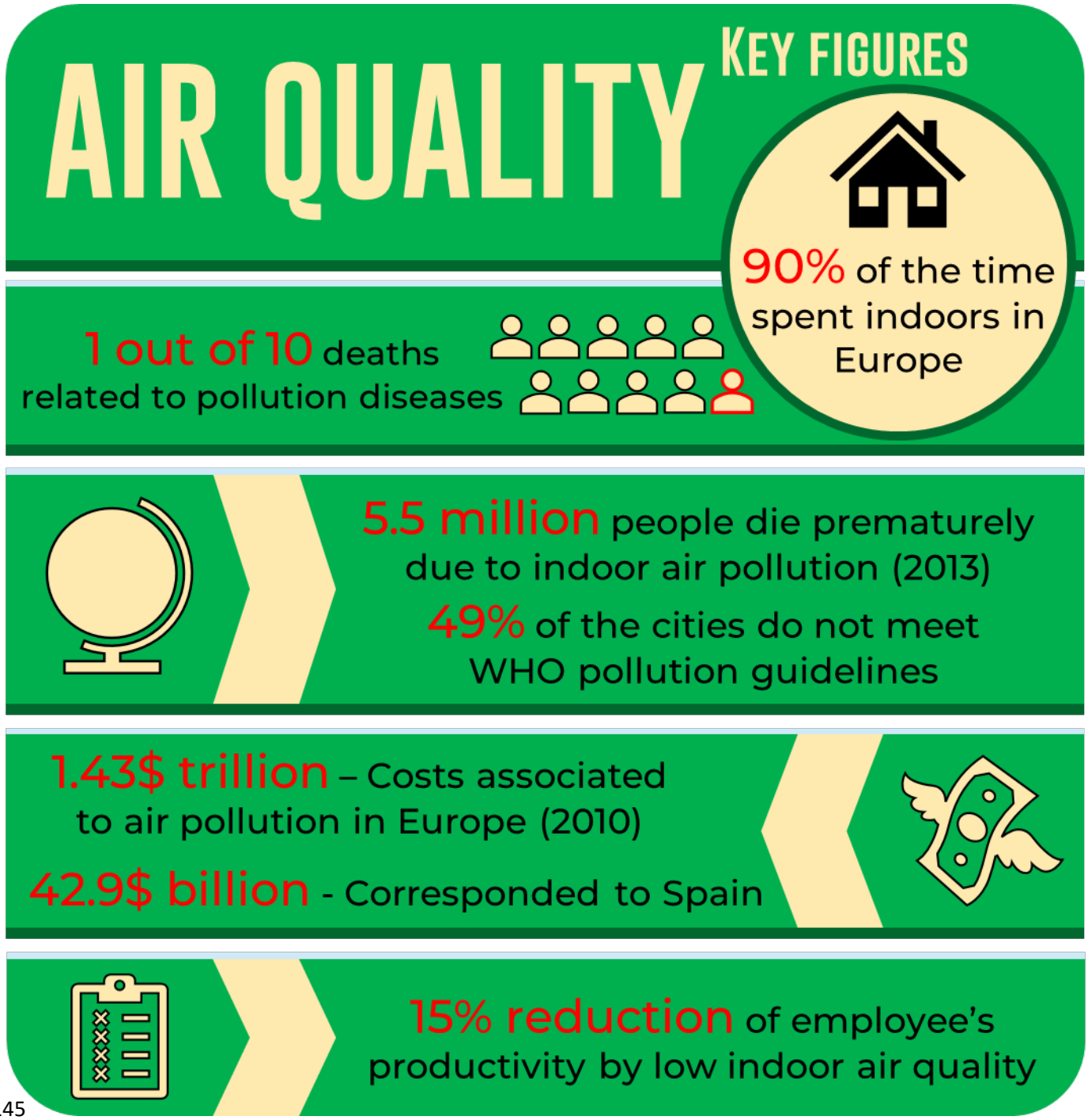


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146 **Figure 1**. Key data of the indoor air quality problem.

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In 2010, the WHO published the first specific IAQ guidelines (World Health Organization and WHO Regional Office for Europe, 2010), which have been since adopted by other organizations in several countries. Whereas these guidelines represented the first attempt to establish a general IAQ standard, only a few priority indoor air pollutants with known adverse health effects were included. Indeed, an exhaustive quantitative regulation comprising all physical, chemical, biological and particulate exposures is rather challenging due to the inherent complexity of indoor air pollution and the lack of information concerning the long-term health effects of each pollutant. In this context, indoor air pollutants include particulate matter, biological pollutants (allergens, bacteria, mold, fungi, spores, etc.), physical agents (temperature, electromagnetic fields) and over 400 different chemical compounds, mainly volatile organic and inorganic compounds (VOCs and VICs, respectively). More recently, organic emerging compounds emitted from plastics, pharmaceuticals or personal care products have been detected in indoor environments. In addition to the wide spectrum of indoor pollutants, their occurrence and concentration depend on many factors such as outdoors air quality, the socio-economic development of the country, type of activities, occupancy, ambient conditions, season of the year, etc. Moreover, pollutant sources and emission rates rapidly change over time (Luengas et al. 2015): endogenous sources include permanent (building materials, adhesives, paints, varnishes, etc.) and occasional sources (furniture, cleaning and disinfection products, cooking, personal care products, human metabolism, etc.), while outdoor pollutants intrusion clearly depends on human activities (road traffic, industry, etc.). Additionally, secondary pollutants might be produced by indoor gas-phase reactions from other compounds present in indoor air (Hubbard et al., 2005; SCHER, 2007).

Unfortunately, there is limited information over IAQ due to the great number of pollutants and sources and their variability. Significant efforts must be undertaken in order to better understand the effects of indoor air pollutants on human health and to design *ad-hoc* regulations to protect human health (Royal College of Physicians, 2016). A better understanding of the type and

concentration of indoor air pollutants will facilitate the design of effective control strategies both in terms of prevention and active abatement. Since prevention must be considered as the first step for improving IAQ, actions have been recently implemented to reduce or eliminate certain pollutant sources. For instance, smoking in workplaces and most public places is prohibited in Europe and many countries in the world, and the use of harmful construction materials such as asbestos or products containing hazardous components like halogenated pesticides is widely restricted (EU Council, 2008). However, pollution control at source is only possible when sources are known, while new substances are constantly detected and classified as hazardous. Therefore, prevention or minimization of indoor pollutant emissions is commonly insufficient, technically non-viable, or economically unfeasible (Guieysse et al. 2008, Luengas et al. 2015). Moreover, according to the Directive 2010/31/EU (European Parliament, 2010), EU Member States have committed to build nearly zero energy buildings by the end of 2020, while enhancing energy performance during major renovations of existing buildings or retrofitting of building elements. New designs devoted to effective energy savings involve airtight, well-insulated and sealed constructions, which substantially reduces natural ventilation. This increase in building air tightness will cause a severe impact on the levels of gas and particulate indoor air pollutants, increasing their concentration as a result of the reduced ventilation rates (Broderick et al. 2017). In this context of potential conflict between energy efficiency measures and enforcement of IAQ standards, the development and optimization of versatile technologies for in-situ indoor air purification is increasingly needed.

## 2. Main pollutants and sources

The most important indoor air pollutants investigated include particulate matter, volatile inorganic compounds and volatile organic compounds. Particulate matter is typically classified as a function of its size, but the most reported value corresponds to the concentration of particles with a mean diameter lower than 2.5 micrometers ($PM_{2.5}$). Carbon dioxide ($CO_2$), carbon

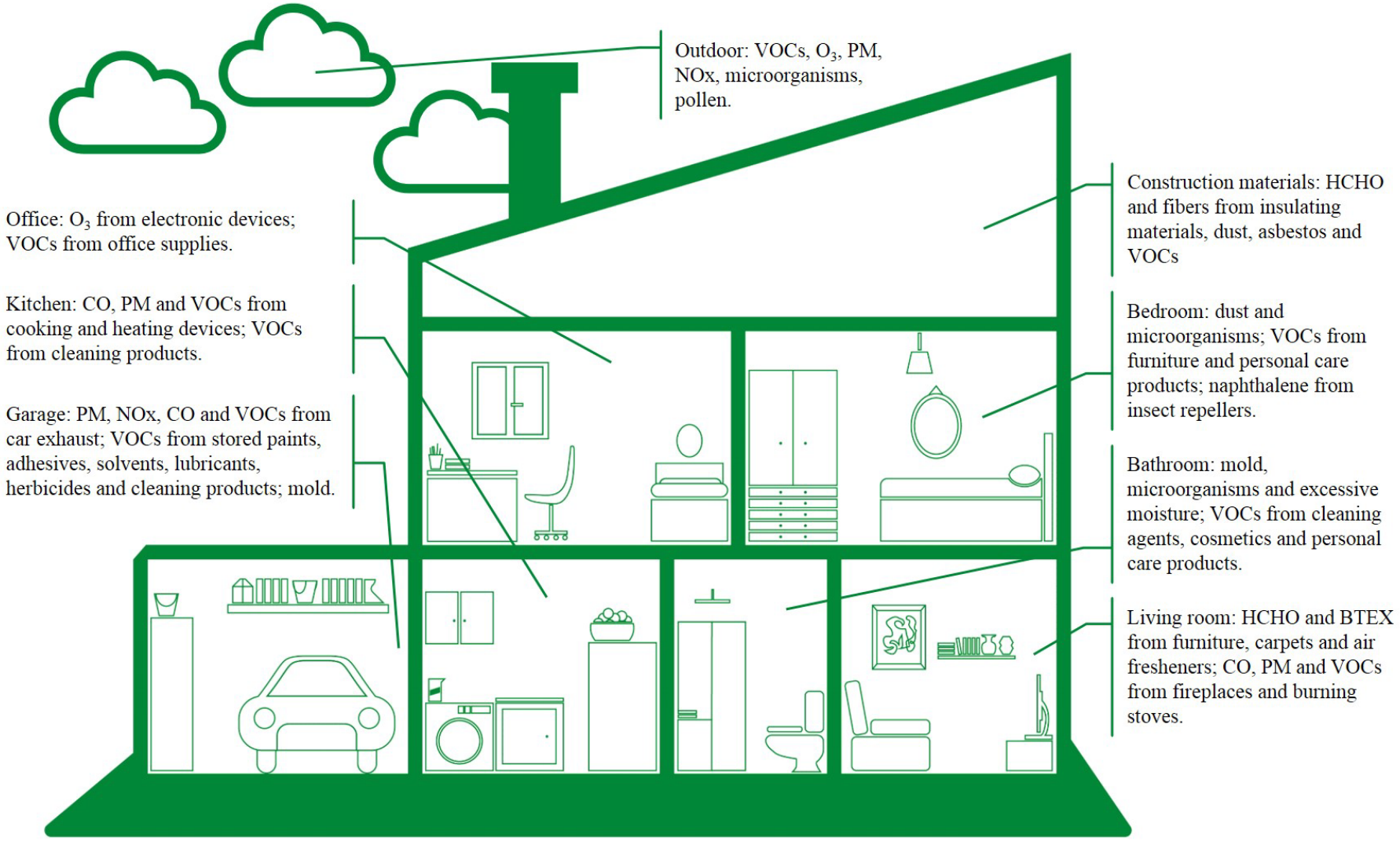
monoxide (CO), nitrogen oxides ($NO_x$) and ozone ($O_3$) rank among the most studied inorganic compounds. VOCs include a wide group of organic gas pollutants with a low boiling point (ranging from 50/100ºC to 240/260ºC) and low vapor pressure ubiquitous in indoor environments (Luengas et al., 2015). This group is continuously growing as new materials are being used in construction and interior design (Figure 2). Despite the large number of pollutants present in indoor environments, only a few of them are typically measured and used as surrogates in order to simplify data acquisition. These surrogate compounds are selected based on their human risk potential or as representative of a more extended group of compounds with similar behaviour. Sampling sites where environmental tobacco smoke (ETS) is present are typically omitted in most monitoring projects since ETS is so dominant over other indoor contaminant sources that results are not reliable (Jantunen et al., 2011).

Research projects investigating indoor air pollution are mainly focused on public and private buildings. These environments are very different in terms of type of pollutants and concentration ranges. Public indoor environments comprise office buildings, schools, shopping centers, libraries, etc., while private indoor spaces involve apartment buildings or detached dwellings. Some studies have investigated the levels of pollutants before and after building renovation, remodeling or refurbishment, which entailed the implementation of new energy-saving concepts and therefore a higher air tightness and accumulation of indoor pollutants. The typical sources (Figure 2), health risks and common concentrations of the most relevant indoor pollutants are here discussed. These pollutants, including PM, VICs (CO, $NO_x$, $O_3$) and VOCs (benzene, toluene, ethylbenzene, xylenes, naphthalene, formaldehyde, trichloroethylene, α-pinene, limonene), have been selected based on their occurrence in indoor spaces or their concerns in terms of human health (Table 1).

| **Compound** | CAS number | Molecular weight **(g/mol)** | Boiling point **(ºC at 1 atm)** | Vapor pressure **(mmHg at 25ºC)** | Water solubility **(mg/L at 25ºC)** | Environmental risks[a] | Henry constant **(mol/m$^3$·Pa)** |
|---|---|---|---|---|---|---|---|
| CO | 630-08-0 | 28.0 | -191.7 | >35 atm | 26.8 at 20ºC | | 9.64E-06 |
| $NO_2$ | 10102-44-0 | 46.0 | 21.0 | 720 | Reacts | | 1.20E-04 |
| $O_3$ | 10028-15-6 | 48.0 | -111.7 | >1 atm | 570 at 20ºC | H400; H410 | 1.10E-04 |
| Benzene | 71-43-2 | 78.1 | 78.8 | 101 | 940.0 | H412; P273 | 1.70E-03 |
| Toluene | 108-88-3 | 92.1 | 110.6 | 27.7 | 320.0 | H412 | 1.50E-03 |
| Ethylbenzene | 100-41-4 | 106.2 | 136.2 | 9.21 | 110.0 | H412 | 1.30E-03 |
| o-xylene | 95-47-6 | 106.2 | 145.9 | 5.99 | 120.0 | H412; P273 | 2.08E-03 |
| m-xylene | 108-38-3 | 106.2 | 140.6 | 7.61 | 99.0 | H412; P273 | 1.37E-03 |
| p-xylene | 106-42-3 | 106.2 | 139.6 | 7.94 | 100.0 | H412 | 1.48E-03 |
| Naphthalene | 91-20-3 | 128.2 | 221.5 | 0.159 | 140.0 | H400; H410 | 2.20E-02 |
| Formaldehyde | 50-00-0 | 30.0 | -19.5 | 3460 | $1.98 \cdot 10^5$ | | 3.20E+01 |
| TCE | 79-01-6 | 131.4 | 87.2 | 72.4 | 390.0 | H412; P273 | 9.50E-04 |
| α-pinene | 80-56-8 | 136.2 | 157.9 | 3.5 | 8.9 | H411 | 2.12E-04 |
| Limonene | 138-86-3 | 136.2 | 175.4 | 1.54 | 3.4 | H400; H410; P273 | 6.27E-04 |

[a]Code: H400: very toxic to aquatic life; H410: very toxic to aquatic life with long lasting effects; H411: toxic to aquatic life with long lasting effects; H412: harmful to aquatic life with long lasting effects; P273: avoid release to the environment

**Table 1**. Physical/chemical properties of the most relevant indoor air pollutants.

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228 **Figure 2**. Main sources of pollutants at homes.

229 Particulate matter consists of solid particles suspended in air able to enter the respiratory tract,
230 which mainly occurs when particle size is below 2.5 micrometers. Natural sources include
231 suspended dust from sand or sea salt, pollen or fire ash, while anthropogenic sources are
232 associated to combustion processes, industry, agriculture and transportation. PM can also be
233 originated by reactions between ozone and some VOCs (e.g. terpenes) (Carazo Fernández et
234 al., 2013; European Environment Agency, 2017; Royal College of Physicians, 2016; SCHER,
235 2007; US Environmental Protection Agency, 1995). Fibers, such as fiber glass and asbestos,
236 can also be included in this group (Carazo Fernández et al., 2013; Leung, 2015; Royal College
237 of Physicians, 2016). Outdoor PM enters indoor environments through ventilation, while indoor
238 sources include combustion-based appliances like ovens, heaters or stoves, and also tobacco
239 smoke and fireplaces (Carazo Fernández et al., 2013; European Environment Agency, 2017;
240 Royal College of Physicians, 2016; SCHER, 2007). When biomass is used as a fuel, indoor
241 levels of PM can exceed those of polluted cities. Long-term exposure to particulate matter can
242 provoke conditions from several respiratory and cardiovascular problems such as eye, nose,
243 throat and bronchial irritation and asthma to fibrosis, anthracosis and lung cancer (Carazo
244 Fernández et al., 2013; Jantunen et al., 2011; Leung, 2015; SCHER, 2007; US Environmental
245 Protection Agency, 1995). Kitchens and bedrooms may exhibit $PM_{2.5}$ concentrations in the
246 range of 25-1526 and 13-27 $\mu g/m^3$, while concentrations of 10-44 and 3-23 $\mu g/m^3$ have been
247 recorded in offices and schools, respectively. Shopping complexes also present high
248 concentrations of $PM_{2.5}$ (74-164 $\mu g/m^3$) (Armendáriz-Arnez et al., 2010; Barmparesos et al.,
249 2018; Broderick et al., 2017; Canha et al., 2017; Datta et al., 2017; Mandin et al., 2017; Pokhrel
250 et al., 2015; Sidhu et al., 2017; Singh et al., 2016; Vasile et al., 2016; Yip et al., 2017).
251 Carbon monoxide is a colorless, odorless, tasteless, non-irritant toxic gas emitted as a result of
252 incomplete combustion processes. CO is usually produced from fossil fuels in power
253 generation, road transportation and heating and cooking devices. However, this pollutant is also
254 emitted by natural sources, accounting for one third of the total emissions. The main indoor

sources of CO are tobacco smoke, defective cooking and heating devices, fireplaces and vehicle gases from attached garages. Outdoor air exchange in dense traffic and parking areas or highly industrialized districts also mediates the intrusion of CO in indoor environments (Carazo Fernández et al., 2013; Kotzias et al., 2005; Leung, 2015; Royal College of Physicians, 2016; Singh et al., 2016; US Environmental Protection Agency, 1995; World Health Organization and WHO Regional Office for Europe, 2010). Inhalation is the main entrance to human body of CO, which is able to bind reversibly to hemoglobin with an affinity 200-250 times higher than oxygen. CO toxic effects are thus based on the interference with $O_2$ transportation through the human body resulting in tissue hypoxia. The extent of health damage depends on the concentration and duration of exposure, and include cardiovascular, respiratory and neurological problems. CO can even cause death under high acute exposure (>1000 $ppm_v$) or long-term exposure (Kotzias et al., 2005; Leung, 2015; US Environmental Protection Agency, 1995; World Health Organization and WHO Regional Office for Europe, 2010). Concentrations of 0.5-17 $ppm_v$, 0.9-3.8 $ppm_v$ and up to 8.5 $ppm_v$ have been recorded in kitchens, bedrooms and shopping areas, respectively (Broderick et al., 2017; Canha et al., 2017; Sidhu et al., 2017; Singh et al., 2016; Vasile et al., 2016; Yamamoto et al., 2014; Yip et al., 2017; Zielinska et al., 2012).

Nitrogen monoxide (NO) and nitrogen dioxide ($NO_2$) are the most common and important nitrogen oxides. These pollutants are generated by combination of oxygen and nitrogen during combustion in power generation industries, transportation and heating systems. NO is produced in a larger extent and is further oxidized to $NO_2$ in the presence of oxygen, ozone or VOCs (European Environment Agency, 2017; World Health Organization and WHO Regional Office for Europe, 2010). The most frequent indoor sources of $NO_x$ are gas appliances like stoves, ovens or water heaters. ETS and fireplaces can also contribute to $NO_x$ emissions (Carazo Fernández et al., 2013; Kotzias et al., 2005; Leung, 2015; Luengas et al., 2015; Royal College of Physicians, 2016; Singh et al., 2016; US Environmental Protection Agency, 1995; World

281 Health Organization and WHO Regional Office for Europe, 2010). Infiltration from outdoor air
282 strongly influences indoor levels, in particular within short distance from roadways or high-
283 density industrial areas. Inhaled $NO_2$ is converted to nitric acid in the lungs, with the associate
284 damage to cells and to the immune system. Inhalation can cause respiratory malfunctioning
285 when other pathologies are previously present (limit for protection of asthmatic of 200 $\mu g/m^3$
286 1-h average; $\approx$2000 $\mu g/m^3$ impact normal individuals). $NO_2$ can cause also eye irritation by
287 direct contact (Carazo Fernández et al., 2013; Kotzias et al., 2005; Leung, 2015; US
288 Environmental Protection Agency, 1995; World Health Organization and WHO Regional
289 Office for Europe, 2010). Concentrations of 5-17 $\mu g/m^3$, 16-18 $\mu g/m^3$ and up to 30 $\mu g/m^3$ have
290 been measured in houses, offices and shopping areas, respectively (Broderick et al., 2017;
291 Langer et al., 2015; Mandin et al., 2017; Prasauskas et al., 2016; Singh et al., 2016; Vasile et
292 al., 2016).
293 Benzene is an organic volatile compound with a characteristic aromatic odor and widely used
294 in industry as a solvent and in the synthesis of several plastics, resins and pharmaceuticals.
295 Outdoor air intrusion contributes to indoor levels, with benzene originated by traffic road and
296 industrial activity (European Environment Agency, 2017; Jantunen et al., 1998; World Health
297 Organization and WHO Regional Office for Europe, 2010). Indoor sources of benzene include
298 ETS, combustion devices and construction materials such as polymeric furnishings, carpets,
299 paints, solvents and wooden furniture (Campagnolo et al., 2017; Carazo Fernández et al., 2013;
300 Jantunen et al., 1998; Kotzias et al., 2005; Royal College of Physicians, 2016; SCHER, 2007;
301 Singh et al., 2016; World Health Organization and WHO Regional Office for Europe, 2010).
302 Benzene (and other pollutants) emissions from these materials decay with time, thus levels are
303 much higher in new or renovated buildings. Health risks for acute intoxication are low (e.g.
304 headaches for 5-h exposure to 150-500 $mg/m^3$), although benzene is a proven carcinogenic and
305 genotoxic chemical under chronic exposure. Benzene can also induce blood illnesses and
306 neurological and reproductive problems (Carazo Fernández et al., 2013; Kotzias et al., 2005;

307 Leung, 2015; World Health Organization and WHO Regional Office for Europe, 2010). No
308 safe level of exposure is recommended. The highest level of benzene has been recorded in
309 shopping areas (2.5-48 μg/m$^3$) followed by offices (1.4-5.5 μg/m$^3$), homes (0.7-4.4 μg/m$^3$) and
310 schools (0.5-3 μg/m$^3$) (Broderick et al., 2017; Dodson et al., 2008; Du et al., 2015; Edwards et
311 al., 2001; Geiss et al., 2011; Kotzias et al., 2009; Langer et al., 2015; Rösch et al., 2014; Singh
312 et al., 2016; Xu et al., 2016; Zielinska et al., 2012).
313 Toluene is also an aromatic compound used in several industrial processes and emitted also by
314 power generation industries and traffic (Campagnolo et al., 2017; Jantunen et al., 1998; Kotzias
315 et al., 2005; Leung, 2015; Royal College of Physicians, 2016). Toluene, present in gasoline,
316 paints, resins, adhesives, cosmetics and coatings, is one of the most common indoor air
317 pollutants and the most abundant among BTEX (benzene, toluene, ethylbenzene and xylene).
318 Indoor sources are infiltration from outdoor air, tobacco smoke, combustion devices and a
319 variety of household products (Carazo Fernández et al., 2013; Jantunen et al., 1998; Kotzias et
320 al., 2005; Royal College of Physicians, 2016; SCHER, 2007; Singh et al., 2016). Toluene is not
321 a confirmed carcinogenic substance, and therefore no long-term health effects have been
322 studied yet. Exposure to toluene increases risks of developing asthma and other respiratory
323 conditions, while short and long-term exposure can affect central nervous system (Kotzias et
324 al., 2005). Shopping complexes present the highest toluene concentrations (15-164 μg/m$^3$),
325 followed by offices (6-32 μg/m$^3$) and homes (3-20 μg/m$^3$). The presence of toluene in schools
326 is marginal (1.8 μg/m$^3$). Concentrations are typically higher in new or recently renovated
327 buildings as a result of the new installed materials (Broderick et al., 2017; Dodson et al., 2008;
328 Du et al., 2015; Edwards et al., 2001; Geiss et al., 2011; Langer et al., 2015; Mandin et al.,
329 2017; Rösch et al., 2014; Singh et al., 2016; Xu et al., 2016; Zhong et al., 2017; Zielinska et al.,
330 2012).
331 Ethylbenzene is a colorless liquid compound at ambient temperature, with a strong gasoline-
332 like scent. Sources of pollution include plastics, paints, adhesives and other products where

ethylbenzene is used as a solvent during manufacturing. Ethylbenzene is also emitted during combustion processes such as traffic (ethylbenzene is included in gasolines), heating devices and cooking (Campagnolo et al., 2017; Jantunen et al., 1998; Leung, 2015; Singh et al., 2016). Acute effects at relatively high concentrations include eye and throat irritation and dizziness. No long-term effects have been described yet in humans. Ethylbenzene has been classified as a potential human carcinogen by the International Agency for Cancer Research (ATSDR, 2007). Concentrations of ethylbenzene up to 16 $\mu g/m^3$ have been detected in offices and shopping complexes. On the other hand, homes and schools exhibit maximum concentrations of 8 and 0.2 $\mu g/m^3$, respectively (Broderick et al. 2017; Dodson et al. 2008; Edwards et al. 2001; Rösch et al. 2014; Singh et al. 2016; Xu et al. 2016; Zhong et al. 2017; Zielinska et al. 2012).

Xylene is a colorless liquid at room temperature with an aromatic odor present as three isomers: ortho, meta and para (*o*-, *m*- and *p*-, respectively). Xylene is used as a solvent in industry and as an additive in gasoline. Indoor sources of xylenes include paints, adhesives, dyes, polymers, cleaning products and pharmaceuticals. Outdoor air is also a source of indoor pollution if dense traffic or industrial facilities using xylene are nearby (Campagnolo et al., 2017; Jantunen et al., 1998; Kotzias et al., 2005; Leung, 2015; SCHER, 2007; Singh et al., 2016). An acute exposure to xylene can cause eye and throat irritation, headache and nausea. Long-term exposure is associated with problems in the respiratory, gastrointestinal and central nervous systems, lungs, kidney, heart and reproductive system. Xylene is a suspected carcinogenic chemical, associated with an increased risk of leukemia, non-Hodgkin's lymphoma and colon/rectum cancer (Kotzias et al., 2005). Shopping areas, with levels ranging from 1.3 to 74 $\mu g/m^3$, and offices, with levels of 2.2 to 16 $\mu g/m^3$, rank among the most polluted sites. Maximum xylene concentrations of 3.1 and 0.3 $\mu g/m^3$ have been measured at homes and schools (Broderick et al. 2017; Dodson et al. 2008; Edwards et al. 2001; Geiss et al. 2011; Langer et al. 2015; Mandin et al. 2017; Singh et al. 2016; Vasile et al. 2016; Xu et al. 2016; Zhong et al. 2017; Zielinska et al. 2012).

359 Naphthalene is a white crystalline solid at ambient temperature, with a characteristic aromatic
360 odor (mothballs), widely used as a raw material in the chemical industry. The main emission
361 source is traffic as a result of the inherent presence of naphthalene in gasoline and diesel. Indoor
362 sources include tobacco smoke, defective combustion devices, herbicides, rubber materials and
363 insect repellents (usually contaminating clothes) (Kotzias et al., 2005; Royal College of
364 Physicians, 2016; World Health Organization and WHO Regional Office for Europe, 2010).
365 Outdoor air is a mayor source in high-traffic and industrial areas. Inhalation is the principal
366 naphthalene intake mechanism in humans, although accidental ingestions of mothballs have
367 been reported. Acute naphthalene intoxication can induce hemolytic anemia and cataracts. No
368 long-term adverse health effects or evidence of human carcinogenicity or genotoxicity have
369 been reported (Kotzias et al., 2005; World Health Organization and WHO Regional Office for
370 Europe, 2010). Naphthalene concentrations ranging from 3 to 26 $\mu g/m^3$ have been recorded at
371 homes (Du et al. 2015; Xu et al. 2016; Zhong et al. 2017).
372 Formaldehyde (HCHO) is a colorless, odorous, highly reactive gas emitted during incomplete
373 reaction of hydrocarbons in industries, traffic and other processes. Formaldehyde is also
374 produced by oxidation of other VOCs with ozone or radiation (Campagnolo et al., 2017; Kotzias
375 et al., 2005; US Environmental Protection Agency, 1995; World Health Organization and WHO
376 Regional Office for Europe, 2010). This chemical is widely used in resins, glues, paints, paper
377 products, cosmetics, electronic equipment, cleaning agents or fabrics. Formaldehyde is present
378 in construction materials such as insulation foams of wooden-based materials employed in
379 floorings or furniture. However, emissions from these materials (e.g. plywood, particleboard or
380 fiberboard) usually decay within several weeks (Carazo Fernández et al., 2013; Jantunen et al.,
381 1998; Kotzias et al., 2005; Royal College of Physicians, 2016; World Health Organization and
382 WHO Regional Office for Europe, 2010). Formaldehyde is rapidly absorbed by the respiratory
383 or gastrointestinal system. Acute exposure effects include odor, irritation, headache and
384 eczema. Formaldehyde is a known carcinogenic and genotoxic chemical, whose long-term

385 exposure can originate nasopharyngeal cancer and myeloid leukemia (Kotzias et al., 2005; US
386 Environmental Protection Agency, 1995; World Health Organization and WHO Regional
387 Office for Europe, 2010). The level of exposure in homes, offices and schools is comparable
388 (7.7-30, 8-17, 9-17 μg/m$^3$) (Broderick et al., 2017; Canha et al., 2017; Dodson et al., 2008;
389 Geiss et al., 2011; Kotzias et al., 2009; Langer et al., 2015; Mandin et al., 2017; Prasauskas et
390 al., 2016; Zhong et al., 2017; Zielinska et al., 2012).
391 Trichloroethylene (TCE) is a volatile chemical with sweet chloroform odor, widely produced
392 by the industry, and used as solvent and cleaning agent (vapor degreasing of metals). TCE can
393 be present in contaminated waters and soils, which could indirectly contribute to indoor levels.
394 Indoor sources include products where TCE is used as solvents such as lubricants, varnishes,
395 paint removers, adhesives and typewriter correction fluids. TCE can be also present in some
396 bleach household products and other cleaning agents (Jantunen et al., 1998; Singh et al., 2016;
397 World Health Organization and WHO Regional Office for Europe, 2010). Human exposure to
398 this VOC occurs by dermal absorption, ingestion and inhalation. Exposure to TCE is often
399 intermittent, as the products that contain this pollutant are not constantly used. Acute exposure
400 to TCE affects the central nervous system at concentrations of ~270 mg/m$^3$, causing a reduced
401 sensorial capacity. TCE is a carcinogenic chemical under long-term exposure, and a chronic
402 exposure may cause liver, kidney and bile duct cancer and non-Hodgkin's lymphoma.
403 Therefore, no safe threshold is recommended due to its carcinogenicity (World Health
404 Organization and WHO Regional Office for Europe, 2010). TCE concentrations ranging from
405 0.3 to 0.6 μg/m$^3$ are typically recorded at homes, and from 0.6 to 4.7 μg/m$^3$ in shopping
406 complexes (Dodson et al., 2008; Edwards et al., 2001; Mandin et al., 2017; Singh et al., 2016;
407 Xu et al., 2016).
408 Alpha-pinene is a colorless liquid with a strong pine scent. This terpene is naturally present in
409 plants and a common constituent of essential oils. Pinene is used as a solvent in some paints
410 and waterproof substances, and can be found in perfumery products, deodorizers and cleaning

411 products. Pinene emissions can also originate from wooden materials like furniture or flooring,
412 particularly those made from pine wood (Campagnolo et al., 2017; Kotzias et al., 2005; Luengas
413 et al., 2015; Royal College of Physicians, 2016). No significant pinene concentrations are found
414 outdoors, except in forest areas. On the other hand, limited data of pinene health risks is
415 available. While acute exposure to high concentration can produce irritation and inflammation,
416 no chronic exposure risks have been reported yet. Health risks might be expected when ozone
417 or other reactive radicals are present, due to their high reactivity with pinene and other
418 unsaturated molecules (Hubbard et al., 2005; Kotzias et al., 2005; Leung, 2015; SCHER, 2007).
419 These reaction by-products would produce eye and upper airways irritation in a more extended
420 way than pinene itself. The largest pinene concentrations are found at homes (11-32 $\mu g/m^3$) and
421 libraries (10-30 $\mu g/m^3$), while offices and schools exhibit concentrations up to 6.3 and 1.5
422 $\mu g/m^3$, respectively (Dodson et al. 2008; Edwards et al. 2001; Geiss et al. 2011; Langer et al.
423 2015; Mandin et al. 2017; Rösch et al. 2014; Xu et al. 2016; Zhong et al. 2017).
424 Limonene is a natural terpene present as two isomers (*d*- and *l*-), which have citric and pine
425 scent, respectively. Limonene is used in a wide variety of household products like cleaning
426 agents, resins, air fresheners, deodorants, fragrances and shampoos (Campagnolo et al., 2017;
427 Kotzias et al., 2005; Luengas et al., 2015; Royal College of Physicians, 2016). This terpene is
428 also found in food as an additive due to its citric odor and flavor. Limonene intake occurs by
429 inhalation or ingestion. This pollutant has low acute toxicity, no symptoms further than eye or
430 skin irritation have been described. Chronic health effects for limonene have not been studied,
431 and there is no evidence of carcinogenicity or genotoxicity. Heath risks are associated to
432 ambient reaction with ozone or reactive radicals, which form byproducts such as aldehydes,
433 carboxylic acids and peroxides, responsible of irritation and odor annoyance at low
434 concentrations (Hubbard et al., 2005; Kotzias et al., 2005; Leung, 2015; SCHER, 2007).
435 Maximum concentrations of 32, 19 and 11 $\mu g/m^3$ have been recorded at homes, offices and
436 schools, respectively (Dodson et al., 2008; Du et al., 2015; Edwards et al., 2001; Geiss et al.,

2011; Langer et al., 2015; Mandin et al., 2017; Rösch et al., 2014; Xu et al., 2016; Zhong et al., 2017).

## 3. Prevention of indoor air pollutant emission

Among the different approaches to control indoor air quality, prevention of pollutant formation and emission rank first in terms of cost-effectiveness. Several strategies to prevent the emission and to decrease the concentration of gas pollutants in indoor environments have been proposed. Overall, ventilation is the easiest measure to prevent the accumulation of indoor pollutants. Indoor pollutant concentrations typically decrease when increasing outdoor air exchange rate unless outdoor pollutant concentrations are high (such as in areas with intense traffic or industrial activities). Mechanical ventilation systems introduce outdoor fresh air into the building, which dilutes the concentration of indoor air pollutants. Some sources can be sealed or removed by professionals, like asbestos and other insulation fibers (Chenari et al. 2016; Kotzias et al. 2005; Leung 2015; Luengas et al. 2015). Smoking bans are also a very effective measure since tobacco smoke is a source of multiple harmful chemicals in elevated concentrations. The suppression of tobacco smoke in indoor places has resulted in consistent IAQ improvements (Kotzias et al., 2005; US Environmental Protection Agency, 1995). Finally, an adequate control of the relative humidity and temperature is crucial to control the emissions of organic pollutants from indoor materials. In this context, air conditioning systems can control the temperature and relative humidity, potentially using smart systems to automatize ventilation or heating depending on the indoor atmosphere (high $CO_2$ levels, low temperatures) or occupants' activities (Chenari et al. 2016; Luengas et al. 2015; Zhou et al. 2017).

Many indoor air pollutants, including PM, BTEX, $NO_x$ or CO, are emitted during combustion processes at homes, such as cooking or heating. Increased ventilation rates and the reduction of these combustion gases from cooking stoves, boilers or fireplaces prevent indoor pollutant accumulation. Combustion devices in buildings must be regularly checked and maintained to

463 prevent malfunctioning and emissions of harmful pollutants to the indoor atmosphere (Carazo
464 Fernández et al., 2013; Leung, 2015; SCHER, 2007; US Environmental Protection Agency,
465 1995). Highly polluting fuels like biomass or kerosene need to be replaced by more efficient
466 fuels such as natural gas or electricity at homes, although there is an increasing popularization
467 of biomass in developed countries due to its higher sustainability. This effect was demonstrated
468 in rural kitchens in Nepal, where emissions of $PM_{2.5}$ from different fuels were investigated. A
469 remarkable improvement in IAQ when using electricity and liquified petroleum gas ($PM_{2.5}$
470 levels of 80 and 101 $\mu g/m^3$, respectively) compared to wood and rice husk ($PM_{2.5}$ levels of 630
471 and 656 $\mu g/m^3$, respectively) (Pokhrel et al., 2015). In addition, improved cooking stoves have
472 been proved to reduce emissions of PM and CO (Armendáriz-Arnez et al., 2010; Sidhu et al.,
473 2017; Yip et al., 2017). Other combustion sources, such as candles or scented incense, may also
474 contribute to a reduced IAQ (Kotzias et al., 2005).
475 Some VOCs are emitted from common construction materials. The manufacture of some
476 wooden-based materials, like plywood or fiberboard, often implies the utilization of resins and
477 varnishes that contain formaldehyde and other VOCs. Paints, glues, plastics and other
478 construction materials include VOCs (usually BTEX) as solvents or additives. Some of these
479 emissions can be prevented by using low-emitting materials like improved plastics and paints
480 (phenol resins instead of urea resins, polyurethane coatings, etc.) and solid wood or old furniture
481 (Carazo Fernández et al. 2013; Environmental Protection Agency 1995; Kotzias et al. 2005;
482 Wei et al. 2015).
483 Occupancy of buildings should be avoided during several weeks after construction or
484 renovation, as pollutant emissions from these sources typically decrease in time until reaching
485 low emission steady state levels. Indeed, pollutant concentrations were found higher even four
486 months after renovation (Broderick et al., 2017). Similarly, emissions of VOCs from paints,
487 adhesives, cleaning products and fuels can be partially mitigated by properly sealing and storing

these liquid materials and minimizing storage periods to prevent leakages and emissions (US Environmental Protection Agency, 1995).

A wide variety of indoor pollutants originate from household and personal care products. Some compounds like pinene and limonene are used as scents in cleaning products, deodorants, cosmetics and even in food (Carazo Fernández et al., 2013; Kotzias et al., 2005; SCHER, 2007). Pollutant emissions can be partially avoided by using household products according to manufacturer instructions (good ventilation, no mixing, being aware of warnings). In addition, unused or nearly empty containers should not be stored for long periods and must be disposed safely (Environmental Protection Agency 1995; Wei et al. 2015).

## 4. Physical-chemical technologies for indoor air treatment

The intrusion or generation of indoor air pollutants cannot always be reduced or suppressed in a cost-effective or technically feasible manner. In these scenarios, active abatement units can be installed in order to lower or eliminate the levels of indoor air contaminants. Traditionally, these devices consisted of physical-chemical technologies such as filters or ozonisers installed as part of a central heating and ventilation system or operated as portable units (Luengas et al., 2015). Real-time sensing has been applied to these devices to optimize their performance. These sensors on-line monitor ambient conditions (temperature, humidity, concentrations of key pollutants) and activate the abatement units based on the need of the occupants and their activities, with the subsequent energy savings (Guyot et al., 2018; Kumar et al., 2016; Tran et al., 2017; Yang et al., 2019). Today, the market of physical/chemical technologies for indoor air treatment is dominated by mechanical and electronic filtration, adsorption and ozonation (Tables 2 and 3).

| Design parameters | Air flow ($m^3/h$) | Single pass efficiency (%) | Reference |
|---|---|---|---|
| ***Mechanical filtration*** | | | |
| Multilayer (glass + synthetic fibers) non-woven filter (≈ MERV 16 filter) filter installed in HVAC system 5.08cm depth | 2.5 m/s | Black Carbon: 88% / Ultrafine PM: 86%<br>PM(0.3-2.5 μm): 91% / PM(>2.5 μm): 88% | (Polidori et al., 2013) |
| MERV16 filter + 12 gas-phase filters + particle postfilter<br>Dimensions: 0.41$m^2$ ×1.95m (portable) | 1362 | Black Carbon: 90% / Ultrafine PM: 94%<br>PM(0.3-2.5 μm): 92% / PM(>2.5μm): 75% | (Polidori et al., 2013) |
| PVC/PU fibers (8 w/w%) on filter paper support<br>Membrane: 100 $cm^2$, 20.72 $g/m^2$ | 1.91 / 5.01 | PM (0.3-0.5 μm): >99.5% | (Wang et al., 2013) |
| Polyester filter with sericin coating | 145 | PM(2.5,10 μm): ≈56% | (Verma et al., 2019) |
| ZIF8-SiO2 nanofiber composite membrane (2h growing time)<br>Dimensions: Ø30mm disc (7.07$cm^2$) | 0.05 | Soft smoke PM: > 99.95% | (Zhu et al., 2019) |
| Double layer nonwoven filter: PP-g-DMAEMA (Dimethylaminoethylmethacrylate)-rGO (reduced graphene oxide) (6.3%) + PP-g-DMAEMA sheet<br>Filter: 25$g/m^2$ | 19.2 | 65% (PP-DMAEMA-rGO)<br>76.4% (PP-DMAEMA)<br>72.2% (Double Layer) | (Tang et al., 2020) |
| ***Electronic filtration*** | | | |
| Ion-spray with carbon fiber electrodes (charger and plates)<br>Charger outside-mounted (emit ions to ambient air)<br>Dimensions: 120×185×85$mm^3$ | 120 | PM (0.3μm; laboratory): 47.8%<br>PM (0.3μm; real chamber): 39.8% | (Sung et al., 2019) |
| Electrostatic precipitator based on corona discharge and parallel plates | 120 | PM (0.3/0.5/1/3): 67.7/67.7/40.6/14.5% | (Zeng et al., 2020) |

**Table 2**. Performance of physical-chemical technologies for the removal of particulate matter.

| Design parameters | Air flow ($m^3/h$) | Pollutant Removal Capacity | Single Pass Efficiency (%) | Reference |
|---|---|---|---|---|
| | | ***Adsorption*** | | |
| Indoor passive panels<br>(gypsum based; different treatments)<br>Dimensions: 0.089 $m^2$ | 0.2 | HCHO: 40-140 $\mu g/m^2 \cdot h$<br>Toluene: 30-210 $\mu g/m^2 \cdot h$ | - | (Zuraimi et al., 2018) |
| Granular activated carbon<br>Ø46mm, 150mm tube ; 7.0 g of adsorbent<br>Thermal desorption (300ºC) | 0.06 | - | Benzene: 81.5-91.6<br>Toluene: 86.6-100<br>Ethylbenzene: 91.6-99.2<br>Xylene: 89.9-100 | (Jo and Yang, 2009) |
| Porous ferrihydrite/$SiO_2$ composite (different aging times) ; 0.27g of adsorbent in Ø140mm petri | - | HCHO: 6.30-8.11 mg/g<br>6mg/g after 7 cycles | | (Xu et al., 2013) |
| Polyester filter with sericin coating | 145 | - | Benz: 2.96 ; Tol: 2.96<br>Et-Benz: 3.71 ; Xyl: 4.18 | (Verma et al., 2019) |
| Carbon nanotubes (LNCT) and carbon microspheres (LCM)<br>Dimensions: Ø16mm, 90mm ; Adsorbent: 3g | 0.001 | Tol / Et-Benz / *o*-xyl<br>LCNT: 52.2, 78.0, 102 mg/g<br>LCM: 47.1, 64.0, 62.7 mg/g | Tol / Et-Benz / *o*-xyl<br>LCNT: 57.8, 47.5, 61.8<br>LCM: 51.7, 53.5, 52.6 | (Srivastava et al., 2019) |
| Alkaline-treated carbon nanotubes (LNCT) and carbon microspheres (LCM)<br>Dimensions: Ø16mm, 90mm ; Adsorbent: 2g | 0.001 | Tol / Et-Benz / *o*-xyl<br>LCNT: 1821, 964, 1076 mg/g<br>LCM: 1093, 895, 996 mg/g | Tol / Et-Benz / *o*-xyl<br>LCNT: 84.0, 83.3, 82.6<br>LCM: 82.5, 83.4, 74.8 | (Srivastava et al., 2019) |
| High-grade activated carbon filter (portable) | 510 | | HCHO: 0.6 ; Toluene: 32.0<br>n-decane: 40.0<br>Tetrachloroethylene: 31.3 | (Chen et al., 2005) |
| Activated carbon prefilter (portable) | 569 | | HCHO: 0.2 ; Toluene: 7.8<br>n-decane: 12.5<br>Tetrachloroethylene: 6.0 | (Chen et al., 2005) |

| | | | | |
|---|---|---|---|---|
| Carbon-zeolite mixture impregnated with potassium iodide (29.5 kg) | 272 | | HCHO: 4.0 ; Toluene: 19.4<br>n-decane: 31.3<br>Tetrachloroethylene: 33.1 | (Chen et al., 2005) |
| Activated charcoal filter (portable) | 225 | | HCHO: 0.4 ; Toluene: 5.6<br>n-decane: 6.0<br>Tetrachloroethylene: 5.2 | (Chen et al., 2005) |
| Non-woven polyester filter (2 layers) impregnated with activated carbon (portable) | 340 | | HCHO: 1.5 ; Toluene: 26.0<br>n-decane: 62.0<br>Tetrachloroethylene: 22.5 | (Chen et al., 2005) |
| Granular activated carbon + $KMnO_4$-impregnated alumina (in-duct) | - | | HCHO: 1.4 ; Toluene: 3.5<br>n-decane: 3.4<br>Tetrachloroethylene: 3.3 | (Chen et al., 2005) |
| ***Photocatalytic oxidation*** | | | | |
| Indoor passive panels + UV-Vis light ($TiO_2$-wood flooring; wallpaper; fabric) Dimensions: 0.089 $m^2$ | 0.2 | Toluene: 59-120 $\mu g/m^2 \cdot h$ ;<br>58-70 $\mu g/m^2 \cdot h$ ; <15 $\mu g/m^2 \cdot h$ | | (Zuraimi et al., 2018) |
| Roofing tiles (three types) and corrugated sheets containing $TiO_2$ (143$cm^2$ ; 12.1-46.4 mg/$cm^2$ and 90$cm^2$; 22.2 mg/$cm^2$, respectively) | - | Toluene (RT / CS):<br>308-512 $\mu g/m^2 \cdot h$ at RH47%<br>248 $\mu g/m^2 \cdot h$ at RH47% | Toluene (RT /CS):<br>28.2-62.9 at RH47% ; 78±2% at RH1%22.7 at RH47% | (Demeestere et al., 2008) |
| UV light (253.7 nm) $TiO_2$ converter (+MERV11 filter) (in-duct) | 720 | | Benz: 0.58; Tol: 0.58;<br>Et-Benz: 0.50; Xyl:0.32;<br>EtOH: 0.19%; n-hex: 0.26;<br>HCHO: 0.08 | (Kadribegovic et al., 2011) |
| UV light (253.7 nm) $TiO_2$ converter (+MERV11 filter) (in duct) | 3600 | | $O_3$ (UV off ): <2<br>$O_3$ (UV on): 15 | (Kadribegovic et al., 2011) |
| ZnO nanorod-wrapped PTFE nanofiber antibacterial membrane with Ag nanoparticles Ø30mm (7.07$cm^2$) ; 0.1mm thick | Bacteria: 0.06<br>HCHO: 0.013 | HCHO: 1989 $\mu g/m^2 \cdot h$ | Bacteria: >99<br>HCHO: ≈60 | (Feng et al., 2017) |

| | | | | |
|---|---|---|---|---|
| Cellulose/Polyester/Polyamide filter coated with P25 $TiO_2/SiO_2$ as catalyst (in duct)<br>Filter: 400$cm^2$, 250 µm thick, 17g/$m^2$ $TiO_2$ | 25.8 | Toluene: 15687 µg/$m^2$·h<br>n-decane: 15071 µg/$m^2$·h<br>TCE: 1646.9 µg/$m^2$·h | Toluene: 8.63<br>n-decane: 5.76<br>TCE: 0.17 | (Héquet et al., 2018) |
| VUV lights + $MnO_x/TiO_2$ on Ni foam catalyst<br>Photocatalyst: 834$cm^2$, 8mm thick | 120 | | TVOC (UV off/on): 50.14 / 74.86 | (Zeng et al., 2020) |
| Polyacrylonitrile (PAN)-$TiO_2$ filter at different designs (simple membrane ; monolith ; truncated cone ; corrugated) ; Properties ($cm^2$, g/$cm^2$): 30, 0.33 ; 198, 0.48 ; 136, 0.23 ; 121, 1.01 | 9.5 | Acetaldehyde<br>Membrane: 2300 mg/$m^2$·h<br>Monolith: 2228 mg/$m^2$·h<br>Trunc. cone: 2300 mg/$m^2$·h<br>Corrugated: 3414 mg/$m^2$·h | Acetaldehyde<br>Membrane: 5.36%<br>Monolith: 4.43%<br>Truncated cone: 5.36%<br>Corrugated: >4.99% | (Roso et al., 2019) |
| Two honeycomb monoliths coated with $TiO_2$ as catalyst + 3 UV lamps (in-duct) | - | | HCHO: 1.6 ; Toluene: 1.8<br>n-decane: 2.5<br>Tetrachloroethylene: 0.7 | (Chen et al., 2005) |
| $SiO_2/TiO_2$-coated glass fiber tissue<br>6.5g/m2 $SiO_2$ + 6.5g/m2 $TiO_2$<br>Ø76mm in-coated tube | 2 | | Benzene: ≈30<br>Propionic acid: ≈49.8 | (Zadi et al., 2020) |
| ***Non-thermal plasma*** | | | | |
| Post-catalytic plasma with different catalysts (Pt/$Al_2O3$, Cu-Mn/$TiO_2$, $Fe_2O_3$+$MnO_2$, CuO+$MnO_2$) and energy densities (J/L)<br>Ø42mm tube; 15g of catalyst | 0.6 | | Toluene (all catalyst): >90 at RH0%, 2.5J/L<br>Toluene (Pt/Al2O3): 39-61 at RH30-72%, 10J/L<br>O3 (Pt/Al2O3): ≈90 at all RH | (Van Durme et al., 2009) |
| Dielectric barrier discharge NTP<br>Dimensions: Ø12mm, 20mm tube<br>(exposure time of 0.06 / 0.12s) | Bacteria: 0.75<br>Fungi: 1.71 | | Bacteria: >95<br>Fungi: 85-98 | (Liang et al., 2012) |
| Dielectric barrier discharge NTP<br>6.5g/$m^2$ SiO2 + 6.5g/$m^2$ $TiO_2$<br>Ø76mm in-coated tube | 2 | | Benzene: 29-52<br>Propionic acid: 10.3-34.7 | (Zadi et al., 2020) |

| | | | | |
|---|---|---|---|---|
| ***Hybrid methods*** | | | | |
| Activated carbon (Jo et al.) + PCO device<br>Inner surface Ø20mm tube, 0.5mg/cm$^2$ of $TiO_2$<br>Thermal desorption (300ºC) | 0.06 | | Benzene: 95.0-98.7<br>Toluene: 97.5-100<br>Ethylbenzene: 98.3-100<br>Xylene: 96.6-100 | (Jo and Yang, 2009) |
| Plasma deodorization unit + Activated charcoal filter (portable) | 408 | | HCHO: 1.2 ; Toluene: 6.7<br>n-decane: 9.6<br>Tetrachloroethylene: 5.8 | (Chen et al., 2005) |
| Electronic cell + Activated carbon postfilter (portable) | 544 | | HCHO: 0.3 ; Toluene: 2.0<br>n-decane: 8.1<br>Tetrachloroethylene: 1.5 | (Chen et al., 2005) |
| High intensity UV lamp + Photocatalytic semiconductor + Pleated activated carbon filter (in-duct) | - | | HCHO: 3.0 ; Toluene: 42.1<br>n-decane: 44.8<br>Tetrachloroethylene: 46.6 | (Chen et al., 2005) |
| ZIF8-$SiO_2$ nanofiber composite membrane<br>Dimensions: Ø30mm disc (7.07cm$^2$) | 0.013 | HCHO:<br>36.04 μg/m$^2$·h; 48.87mg/g | HCHO: ≈80 | (Zhu et al., 2019) |
| Dielectric barrier discharge NTP + UV light + $SiO_2$/$TiO_2$-coated glass fiber tissue<br>6.5g/m$^2$ SiO2 + 6.5g/m$^2$ TiO2<br>Ø76mm in-coated tube | 2 | | Benzene: 58-90<br>Propionic acid: 63.8-94.8 | (Zadi et al., 2020) |
| Electrostatic precipitator + Vacuum-UV lights + $MnO_x$/$TiO_2$ on Ni foam catalyst + $MnO_2$ catalyst for $O_3$ removal<br>$MnO_x$/$TiO_2$ catalyst: 834cm$^2$, 8mm thick | 120 | | TVOC: 4.04<br>No $O_3$ generation | (Zeng et al., 2020) |
| MOF $TiO_2$/UiO-66-$NH_2$ composites + UV light<br>Toluene exp: 100mg of cat. on 250-mesh screen<br>Acetaldehyde exp: 100mm, Ø6mm tube | 0.06 | Toluene (25/75/90%w $TiO_2$):<br>106.7/164.4/142.0 mg/g<br>$CH_3CHO$: (75%w $TiO_2$):<br>275.3 mg/g | Toluene (25/75/90%w $TiO_2$):<br>47.2/72.7/62.8<br>$CH_3CHO$: (75% w $TiO_2$):<br>70.74 | (Zhang et al., 2020) |

| | | | |
|---|---|---|---|
| Double layer nonwoven filter: PP-g-DMAEMA (Dimethylaminoethylmethacrylate)-rGO (reduced graphene oxide) (6.3%) + PP-g-DMAEMA sheet ; Filter: 25g/m$^2$ | 0.18 | Benzene / Toluene / Xylene PP-DMAEMA-rGO: 51.4 / 50.6 / 48.9 mg/g PP-DMAEMA: <5mg/g each Double layer: 39.1 mg/g overall | (Tang et al., 2020) |

514

515 **Table 3**. Performance of physical/chemical technologies for the removal of VOCs.

516 Mechanical filtration, based on the forced circulation of air through a fibrous material where
517 pollutants are captured, is the simplest and most popular method for PM removal. PM removal
518 efficiencies depend on several factors such as the type and material of the filter or the air flow
519 (Harriman et al., 2019; Luengas et al., 2015). These filters need regular replacements to
520 maintain the capture efficiency, prevent the re-emission of pollutants and to avoid the growth
521 of microorganisms on the organic matter trapped in the filter material (Guieysse et al., 2008).
522 Single pass efficiencies higher than 90% are typically achieved in conventional filters, even at
523 high areal flow rates of 3240 $m^3/m^2h$ (Polidori et al., 2013). New materials such as zeolites
524 (Zhu et al., 2019) or polymers (Tang et al., 2020; Wang et al., 2013) have been tested as
525 effective filters for particulate matter (Table 2).
526 Electronic filtration is based on the attraction of negatively charged particles to a plate with
527 opposite polarity, where particles are retained. Two commercial devices are available:
528 electrostatic precipitators ionizing pollutant particles and ion generators dispersing into the air
529 ions that will subsequently attach to pollutants. This technology exhibits higher capital and
530 operating costs than mechanical filtration (particularly ion generators) and requires an active
531 removal of the particles accumulated on the plates. Electronic filtration also entails the
532 generation of harmful pollutants such as ions, ozone or other compounds from VOCs ionization
533 (Hubbard et al., 2005; Luengas et al., 2015). The efficiencies achieved by electronic filters are
534 lower than those provided by mechanical filtration, and range between 14.5% and 67.7% for
535 different PM size (Zeng et al., 2020) (Table 2).
536 Adsorption consists of the capture of organic and inorganic volatile pollutants on the surface of
537 an adsorbent material. The most popular materials are activated carbon and zeolites, although
538 alumina, silica gel or polymers are also used (Jo and Yang, 2009; Kim and Ahn, 2012; Luengas
539 et al., 2015). These adsorbent materials can be even incorporated in construction materials,
540 which are easy to integrate in interior surfaces (Cros et al., 2012; da Silva et al., 2017; Gall et
541 al., 2011; Zuraimi et al., 2018). A high relative humidity and the inherent variability of pollutant

levels in indoor environments decrease the efficiency of adsorption filters. In addition, the adsorption specificity of the material with one pollutant may inhibit the efficient adsorption of other gas pollutants. These systems can also accumulate microorganisms hazardous to human health. Adsorbent materials need to be periodically replaced or regenerated upon saturation to maintain the efficiency and prevent re-emission, thus increasing operating costs (Guieysse et al., 2008; Luengas et al., 2015). VOC removal efficiencies in adsorption devices are very heterogeneous and dependent on pollutant hydrophobicity (Chen et al., 2005). Nevertheless, removal rates of 90% are achieved for BTEX using activated carbon (Jo and Yang, 2009) and carbon nanocomposites (Srivastava et al., 2019) as adsorbent materials. Removal capacities up to 140 $\mu g/m^2 \cdot h$ (Zuraimi et al., 2018) or 8.11 mg/g (Xu et al., 2013) have been reported for formaldehyde. Likewise, Srivastava et al. achieved retention capacities of 1821, 964 and 1076 mg/g for the removal of benzene, toluene and xylene, respectively (Table 3). Overall, adsorption technologies are considered the best physical/chemical technology to remove indoor VOCs.

Ozonisers generate $O_3$ molecules from ambient $O_2$ by high-voltage discharge or UV radiation . $O_3$ is a strong oxidant that can react with VOCs and VICs present in indoor air. Although the levels of some VOCs may be reduced, the abatement efficiencies of ozonisers are not superior to their physical/chemical counterpart (Luengas et al., 2015). In addition, health problems may arise from high indoor levels of ozone or by hazardous secondary pollutants produced by the reaction of $O_3$ with VOCs, particularly with terpenes (Chen et al., 2005; Hubbard et al., 2005; Luengas et al., 2015). The performance of ozonisers has not been evaluated in this review as they are not recommended for indoor air treatment due to their above-mentioned health risks.

UV photolysis relies on the degradation of VOCs, bacteria, fungi and viruses by ultraviolet radiation. Indeed, this technology constitutes an effective method for sterilization at ambient temperature and pressure (De Robles and Kramer, 2017). However, UV radiation is harmful

568 for human health and only some air pollutants are effectively destroyed. The high cost of lamp
569 acquisition and intensive energy consumption rank among the main disadvantages of this
570 technology. In addition, undesired compounds such as ozone or secondary organic pollutants
571 might be released to indoor air as a result of the unspecific action of UV radiation (Chen et al.,
572 2005; Guieysse et al., 2008; Luengas et al., 2015). The performance of stand-alone photolysis
573 units was not herein evaluated since this technology is commonly implemented as
574 photocatalytic oxidation.
575 Photocatalytic oxidation (PCO) utilizes catalytic semiconductors to create reactive radicals
576 from ambient $O_2$ and radiation (generally UV), which further react with indoor air pollutants.
577 $TiO_2$ is the most popular catalyst due to its low cost, non-toxicity, biocompatibility and
578 effectiveness. Other metallic oxides and sulfides ($SnO_2$, ZnO, CdS) are also used as catalysts
579 (Chen et al., 2005; Mo et al., 2009). This technology can cope with a larger spectrum of
580 pollutants than photolysis (Guieysse et al., 2008). The generation of harmful radicals and
581 secondary organic aerosols, along with the high costs of catalyst media replacement, limit the
582 widespread use of this technology (Chen et al., 2005; Luengas et al., 2015). Single pass
583 efficiencies in photocatalytic devices are pollutant and catalyst specific. For instance, Feng et
584 al. (2017) reported a removal efficiency of 60% for formaldehyde (Feng et al., 2017), while
585 Zeng et al. (2020) reported a 75% removal of TVOC (Zeng et al., 2020). The areal elimination
586 capacity is an important design parameter in PCO, with values as high at 3414 $mg/m^2 \cdot h$ reported
587 for acetaldehyde (Roso et al., 2019) (Table 3).
588 Plasma consists of a cloud of highly ionized gas containing electrons, positive ions, oxidants
589 and free radicals able to degrade organic pollutants, precipitate particulate matter and kill
590 pathogens (Luengas et al., 2015). Non-thermal plasma (NTP) is generated at ambient
591 temperature by high voltage discharges (usually corona discharge) at the expenses of a high
592 energy consumption. Similarly to UV or photocatalytic oxidation, plasma mediates the
593 generation of $O_3$ and other by-products or oxidation intermediates that may be as dangerous for

human health as the parent pollutants (Chen et al., 2005; Luengas et al., 2015). NTP can achieve removal efficiencies of up to 90% for VOCs (Van Durme et al., 2009) and microorganisms (Liang et al., 2012), although operation under real conditions (i.e. high humidity and low pollutant concentrations) could reduce its abatement performance (Table 3).

Membrane separation is based on the transfer of indoor air pollutants to another fluid through a semipermeable membrane. This technology has been consistently proven at high pollutant concentrations, but its efficiency at the low levels of pollutants found in indoor air is not guaranteed (Guieysse et al., 2008). Mechanical resistance and pressure drop, and therefore operational costs, are higher compared to other technologies. In addition, VOCs captured on the other side of the membrane must be appropriately managed or destroyed in a separate unit (Guieysse et al., 2008; Luengas et al., 2015). Membrane separation is still a developing technology in indoor air treatment.

Overall, there is no single physical-chemical technology capable of coping with all indoor air pollutants in a cost-effective manner, which requires the use of sequential technology configurations at the expenses of superior capital and maintenance costs. Mechanical filtration is typically installed to eliminate particulate matter prior to other abatement technology (Luengas et al., 2015). The broad nature of VOCs and VICs requires tandems of gas pollutant abatement technologies. For instance, Jo and Yang (2009) reported removal efficiencies of BTEX of ~100% using a granular activated carbon adsorbent coupled with a PCO-$TiO_2$ unit (Jo and Yang, 2009). Likewise, Zhu et al. (2019) (Zhu et al., 2019)(Zhu et al., 2019)achieved a removal efficiency of 80% for formaldehyde, with an adsorption capacity of 48.9 mg/g (gram of adsorbent) (Zhu et al., 2019). Zhang et al. (2020) recorded capacities of up to 164.4 mg/g for toluene and 275.3 mg/g for acetaldehyde (Zhang et al., 2020), while a capacity of 39.1 mg/g has been reported by Tang et al. (2020) for benzene, toluene and xylene (Tang et al., 2020) (Table 3).

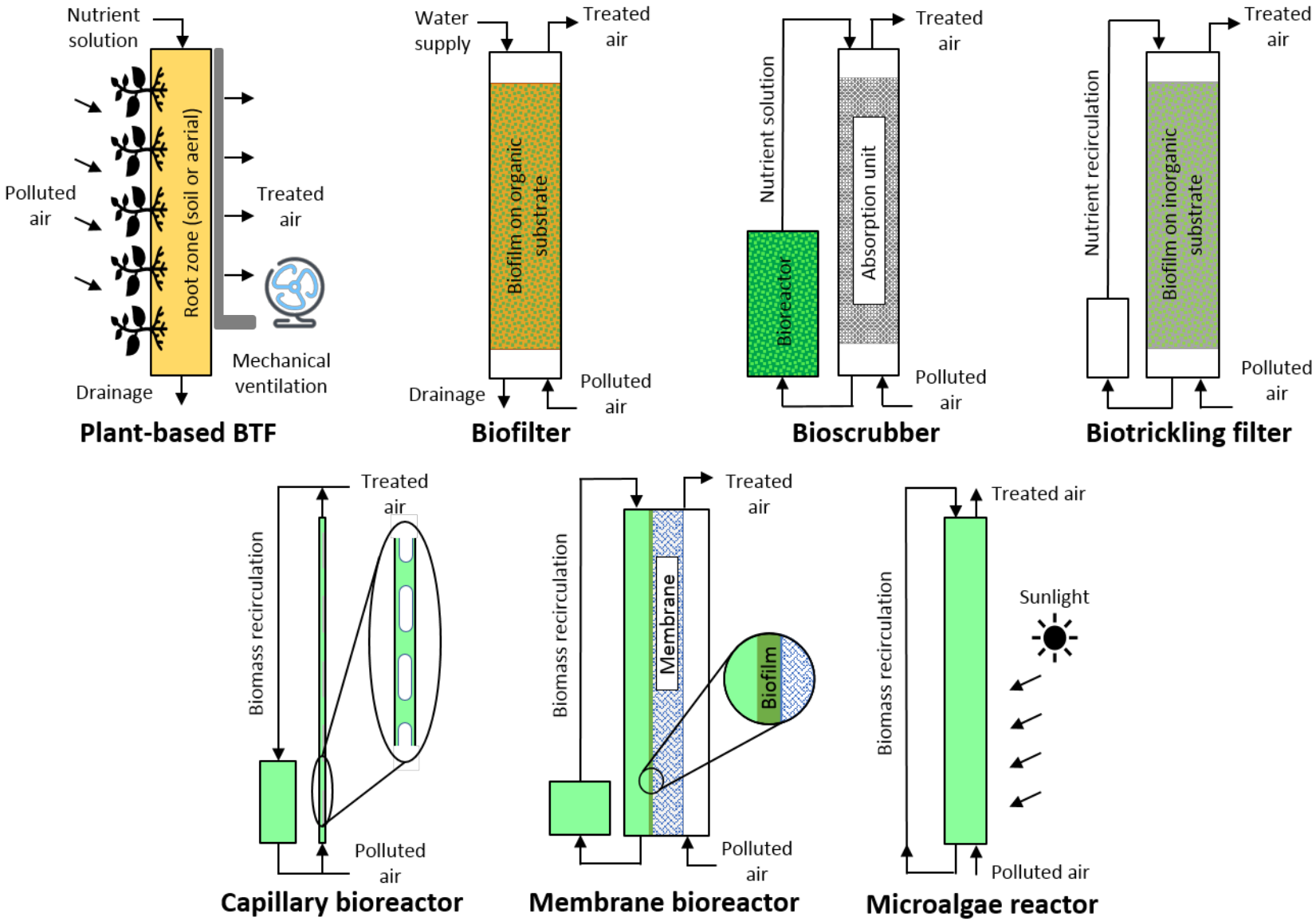
## 5. Biological Based Purification Methods

The performance of conventional physical-chemical methods for indoor air purification is hampered by the low concentrations, the diversity and the variability of VOCs in indoor environments. However, these limitations represent an opportunity for biological based purification systems. Biotechnologies are based on the action of microorganisms or plants, which are able to eliminate or transform the gas pollutants by utilizing them as energy and/or carbon source for either cell maintenance or replication (Guieysse et al., 2008). Overall, indoor air pollutant biodegradation relies on the action of oxidative enzymes, which function at ambient pressure and temperature without the need of additional chemicals. In botanical technologies, both plant and soil microenvironment are responsible of pollutant degradation. On the other hand, gas-water contactors are based on the biocatalytic action of suspended or immobilized microorganisms, which bio-convert air pollutants into $CO_2$, $H_2O$ and new microorganisms. These microorganisms need to be integrated by diverse, versatile and adaptive microbial communities of bacteria, fungi, microalgae or yeasts able to remove simultaneously a wide spectrum of pollutants at variable concentrations without generating undesirable by-products (Soreanu, 2016). Microorganisms are typically present as biofilms, which consist of a moist layer of cells adhered to the surface of a support material. Biofilms provide a protected environment to microorganisms and support a direct contact between the gas pollutants and cells, which enhances pollutant mass-transfer, a commonly limiting parameter in gas-phase bioreactors (Guieysse et al., 2008; Soreanu, 2016; Soreanu and Dumont, 2020).

Biotechnologies have been successfully developed for industrial applications, where varying concentrations of multiple gas pollutants from different sources are cost-effectively treated (Estrada et al., 2011; Kennes and Veiga, 2013; Soreanu and Dumont, 2020; Van Groenestijn and Kraakman, 2005). However, the potential of biotechnologies for indoor air purification remains unexplored due to the particular and challenging conditions of indoor environments (Pacheco-Torgal et al., 2015). Mass-transfer limitations and the rapidly changing

concentrations of a large spectrum of gas pollutants are the main drawbacks associated with indoor air treatment. Additionally, a cost-competitive $CO_2$ removal and the control of biological hazards need to be addressed prior in-house implementation of biotechnologies. Biological-based purification systems for indoor air would improve the energy efficiency of buildings, while providing additional benefits in indoor environmental quality such as aesthetic and psychological improvements (Guieysse et al., 2008; Moya et al., 2019). As indoor environments are often condensed spaces, biotechnologies need to be compact and aesthetically integrated units with high effectiveness treating large air flowrates. In this context, new configurations of bioreactors such as membrane, capillary or two-phase reactors have been successfully tested to maximize the mass-transfer of gas pollutants (Kraakman et al., 2011; Muñoz et al., 2012; Soreanu, 2016). Alternatively, botanical biofiltration could have additional economic, environmental and social benefits, including remarkable psychological impacts of 'greening' the indoor space with plants. In addition, plants are able to effectively decrease $CO_2$ concentration, which has been proved to impact on human decision-making performance (Satish et al., 2012).

The most common technologies for indoor air treatment are discussed below. Furthermore, some examples of these purification methods and their principal operational characteristics are shown in Table 4 and in Figure 3.




664

665 **Figure 3**. Schematic operational configurations of different air purification biotechnologies.

| **Description of the Technology** | Air flow **($m^3/h$)**<br>EBRT **(min)** | Removal Efficiency **(%)**<br>Elimination capacity **($mg/m^3 \cdot h$)** | Inlet concentration<br>Inlet load | Reference |
|---|---|---|---|---|
| | | ***Botanical technologies*** | | |
| Active potted plant: *Epipremnum aureum* (2)<br>Filter bed: 0.35×0.2×0.15 $m^3$, granular activated carbon + shale pebbles (1:1 mixture; Ø5 mm)<br>5.1 $m^3$ chamber | 50 $m^3/h$ | HCHO: 19.9-32.7%<br>at RH55-90% | HCHO: 824±15 $\mu g/m^3$ | (Wang et al., 2014) |
| Biowall: *Philodendron scandens* (18) + *Philodendron scandens* 'Brazil' (13) + *Asplenium antiquum* (19) + *Syngonium podophillum* (13)<br>1.5 $m^2$ module; 30 $m^3$ chamber<br>Support: inorganic media + activated carbon | 50 $m^3/h$ | Butanone: 55.1-58.5% | Butanone:<br>39.4-44.8 $\mu g/m^3$ | (Torpy et al., 2018) |
| | | ***Biofilters*** | | |
| Compost/perlite (75:25) as packing (8.5L)<br>120 cm, Ø10 cm PVC reactor<br>Activated sludge as inoculum | 1.57-0.53 min | $H_2S$: >99%<br>Toluene: >99.9%<br>Butanone: >98.9% | $H_2S$: 23.6-43.3 $mg/m^3$<br>Toluene: 0.40-0.60 $mg/m^3$<br>Butanone: 4.3-6.3 $mg/m^3$ | (Lebrero et al., 2011) |
| Compost as packing<br>2L PVC column (53 cm, Ø8.3 cm)<br>Irrigation flow rates: 30/120 mL/day<br>Activated sludge as inoculum | 0.72/0.30 min | MeSH: >98%; ≈1.2 $g/m^3 \cdot h$<br>Toluene: >98%;≈0.22 $g/m^3 \cdot h$<br>α-pinene: >98%;≈0.25 $g/m^3 \cdot h$<br>n-hexane: 96-98%; ≈0.20 $g/m^3 \cdot h$ | MeSH: 410-980 $mg/m^3 \cdot h$<br>Toluene: 69-164 $mg/m^3 \cdot h$<br>α-pinene: 76-182 $mg/m^3 \cdot h$<br>n-hexane: 63-150 $mg/m^3 \cdot h$ | (Lebrero et al., 2014) |
| Compost/pozzolan (80:20) as packing (3.8L)<br>0.25 m, Ø0.1 m reactor<br>Activated sludge as inoculum | 0.38 min | Toluene: ≈100%; ≈23.9 $mg/m^3 \cdot h$<br>p-xylene: ≈65-100%; ≈14 $mg/m^3 \cdot h$ | Toluene: 0-25 $mg/m^3 \cdot h$<br>p-xylene: 0-22.5 $mg/m^3 \cdot h$ | (Luengas et al., 2017) |
| | | ***Biotrickling filters*** | | |
| *Pseudomonas putida* embedded in calcium alginate gel (granules); 30 cm, Ø6 cm column (4 beds); Liquid flow: 1.23 L/day | 0.09 $m^3/h$ | HCHO: 68.6-93.5%; 25-158.4 $mg/m^3 \cdot h$ | ≈0.2-1.34 $mg/m^3$ | (Lu et al., 2012) |

| | | | | |
|---|---|---|---|---|
| PU foam as packing (2L, 1cm$^3$ cubes); PVC column (53 cm,Ø8.3 cm); Liquid flow: 1.5 m/h<br>Activated sludge as inoculum | 0.07-0.72 min | MeSH: >97%; ≈1.2 g/m$^3$·h<br>Toluene: >97%; ≈0.22 g/m$^3$·h<br>α-pinene: >97%; ≈0.25 g/m$^3$·h<br>n-hexane: 88-95%; ≈0.20 g/m$^3$·h | MeSH: 410-980 mg/m$^3$·h<br>Toluene: 69-164 mg/m$^3$·h<br>α-pinene: 76-182 mg/m$^3$·h<br>n-hexane: 63-150 mg/m$^3$·h | (Lebrero et al., 2014) |
| PU foam as packing (48 cubes; 4×4×4 cm$^3$)<br>Acrylic 8×8×76 cm$^3$ reactor<br>Liquid flow: 0.3/0.5 L/min<br>Activated sludge as inoculum | 0.12/0.30 m$^3$/h<br>1.53/0.61 min | VOCs (normalized carbon content)<br>78-87%; 1.2-9.3 $mg_{carbon}$/m$^3$·h | 1.5-10.7 $mg_{carbon}$/m$^3$·h | (Saucedo-Lucero and Revah, 2018) |
| PE Ralu-rings (1.5×1.5 cm$^2$) as packing (60 cm high); 100 cm, 48L reactor; Liquid flow: 1.2 m$^3$/h<br>Enriched culture inoculum | 3.0-9.0 m$^3$/h<br>0.96-0.32 min | Ethanol: 100%; 5-22 g/m$^3$·h<br>DMS:10-100%; 0.65-6.6 g/m$^3$·h<br>Optimal 95% (low gas flux) | Ethanol: 5-22 g/m$^3$·h<br>DMS: 2.8-8.5 g/m$^3$·h | (Bak et al., 2017) |
| | | | | |
| ***Membrane biotechnologies*** | | | | |
| Porous acrylonitrile support (50µm) + PDMS layer (0.3µm); 40 cm$^2$ membrane in 200×5×2 mm$^3$ (8mL) compartments; Liquid flow: 0.03 L/min<br>Activated sludge + hydrophobic bacteria as inoculum (+ silicon oil); | 1.0-0.12 min | Acetone: 95-100%<br>Toluene: 93-100%<br>n-hexane: 7-28%<br>Limonene: 88-100% | Acetone: 0.1-10.2 mg/m$^3$·h<br>Toluene: 0.2-13.4 mg/m$^3$·h<br>n-hexane: 0.1-5.6 mg/m$^3$·h<br>Limonene: 0.1-9.6 mg/m$^3$·h | (Lebrero et al., 2013) |
| Commercial hollow-fiber membrane reactor (10600 PDMS fibers, Ø190 µm; V: 300 mL; A: 8300 cm$^2$); Liquid flow: 0.2 L/min;<br>Activated sludge as inoculum | 1.4-0.27 min | MeSH: 8.5-98%; ≈0.58 g/m$^3$·h<br>Toluene: 67-99%; ≈0.11 g/m$^3$·h<br>α-pinene: 70-99%; ≈0.12 g/m$^3$·h<br>n-hexane: 38-58%; ≈0.09 g/m$^3$·h | MeSH: 210-1103 mg/m$^3$·h<br>Toluene: 35-185 mg/m$^3$·h<br>α-pinene: 39-205 mg/m$^3$·h<br>n-hexane: 32-169 mg/m$^3$·h | (Lebrero et al., 2014) |
| | | | | |
| ***Hybrid technologies*** | | | | |
| Biofilter + Adsorption system<br>Pyrex column (23 cm, Ø10 cm) packed with compost + Activated carbon adsorption column (2.9 cm, Ø2.5 cm column) | 0.5 m$^3$/h<br>0.22 min (BF)<br>0.002 min (AC) | Toluene: 88.2-98.2% (BF)<br>Toluene: 84.9-99.9% (BF+AC) | Toluene: 17-52 µg/m$^3$<br>(4.2-14 mg/m$^3$·h)<br>Peaks of 733±55 µg/m$^3$<br>(200±20 mg/m$^3$·h) | (Hort et al., 2014) |

| | | | | |
|---|---|---|---|---|
| Biofilter + Adsorption system<br>25 cm, Ø10 cm reactor; Compost/pozzolan (80:20) packing (1.26L) + Activated carbon (1.26L) column<br>Activated sludge as inoculum | 0.13-0.04 min | Toluene: ≈100% (at 45 mg/m$^3$·h), up to 80 mg/m$^3$·h (BF); ≈100%, up to 187 mg/m$^3$·h (AC)<br>p-xylene: ≈100% (at 32 mg/m$^3$·h) up to 32 mg/m$^3$·h ((BF); ≈100%, up to 63 mg/m$^3$·h (AC) | Toluene: 0-235 mg/m$^3$·h<br>p-xylene: 0-63 mg/m$^3$·h | (Luengas et al., 2017) |
| Biofilter + Adsorption system<br>25 cm, Ø10 cm reactor; Compost/pozzolan (80:20) packing (1.26L) + Activated carbon (1.26L) column<br>Activated sludge as inoculum | 0.13-0.04 min | Toluene: 100% at 45 mg/m$^3$·h (BF); 100% at 187 mg/m$^3$·h (AC)<br>p-xylene: 100% at 32 mg/m$^3$·h (BF); 100% at 63 mg/m$^3$·h (AC) | Toluene: 0-235 mg/m$^3$·h<br>p-xylene: 0-63 mg/m$^3$·h | (Luengas et al., 2017) |
| Bag filter + Photocatalytic reactor + BTF<br>Bag filter: 90 cm, Ø60 cm reactor<br>PC: 45×45×100 cm$^3$; 10 UV lamps; 20 Ni foam plates (21.5×25.0 cm$^2$) coated with $TiO_2$<br>BTF: 220 cm, Ø40 cm reactor; ceramic beads/ Raschig rings (50:50) packing; 6×12cm bed layers | 200 m$^3$/h | TVOC: 84% (4+65+15%)<br>PHAs: 87% (18+63+6%)<br>PBDEs: 94% (80+11+3%)<br>% for Bag filter, BTF and PC, respectively | TVOC: 48-920 μg/m$^3$<br>PHAs: 0.94-1.2 μg/m$^3$<br>PBDEs: 0.85-4.8 μg/m$^3$ | (Chen et al., 2016) |

**Table 4**. Performance of biological technologies for the removal of VOCs.

668 Phytoremediation is an established method for the treatment of polluted soils and waters. The
669 application of botanical systems to indoor environments has been shown effective for removing
670 VOCs and PM (Liu et al., 2007; Pacheco-Torgal et al., 2015; Torpy et al., 2014; Wood et al.,
671 2006; Yang et al., 2009). Botanical technologies can be divided into passive (e.g. potted plants)
672 or active (plant-based biotrickling filters, PBTFs) systems. Passive systems rely on the diffusion
673 of gas pollutants, which is a slow process at the low concentrations typically present in indoor
674 environments. Active systems incorporate mechanical ventilation devices to increase the
675 availability of the gas pollutants. In PBTFs, the polluted air is forced to flow though the aerial
676 parts and roots of hydroponic plants to maximize the removal of pollutants. Additional benefits
677 of these active systems such as decreasing indoor temperature, increasing relative humidity or
678 acting as passive acoustic insulation have been identified (Moya et al., 2019). While $CO_2$, $SO_x$,
679 $NO_x$ and $O_3$ appear to be taken up directly through the stomates of plants during daylight, VOCs
680 are mostly degraded by microorganisms present in the rhizosphere. A symbiotic relationship
681 between plants and microorganisms may be achieved (Moya et al., 2019; Oh et al., 2011;
682 Pacheco-Torgal et al., 2015; Torpy et al., 2014; Yang et al., 2009). The performance of
683 botanical technologies is still lower than that of other conventional technologies (Table 4).
684 Alike phytoremediation, biofiltration is a well-known and proven method for the removal of
685 gas pollutants, which can be engineered in multiple configurations (Figure 3). In biofilters
686 (BFs), microorganisms are immobilized in a packing media, traditionally an organic material
687 like compost, irrigation is intermittent, and moisture and nutrients are retained by the biofilm
688 and the packing media. BFs are the preferred option for the treatment of hydrophobic pollutants
689 based on the occurrence of a direct contact between the biofilm and the air emission.
690 Bioscrubbers consist of two separate units, where pollutants are initially transferred in a packed-
691 bed or mist absorption unit from the gas phase to an aqueous phase, which is recirculated to a
692 second unit where microorganisms growing in suspension biodegrade the dissolved pollutants.
693 This configuration provides high abatement efficiencies for hydrophilic pollutants. Biotrickling

694 filters (BTFs) are stand-alone units with packing media, typically inorganic materials with large
695 surface area supporting biofilm growth, with a solution of nutrients continuously trickling down
696 over the packing. BTFs are effective for the treatment of hydrophilic pollutants and typically
697 operate at lower gas residence time than BF or bioscrubbers (Soreanu, 2016; Soreanu and
698 Dumont, 2020). These systems are well-established technologies for air pollution control in
699 many industrial applications, providing an effective abatement performance, reliability and low
700 operating costs (Estrada et al., 2011; Kennes and Veiga, 2013; Soreanu and Dumont, 2020; Van
701 Groenestijn and Kraakman, 2005). Table 4 highlights the performance of BFs and BTFs
702 operating at the concentration range commonly found in indoor air. Removal efficiencies higher
703 than 95 % at gas residence times lower than 95 s have been reported in BFs and BTFs for a
704 wide range of pollutants.
705 Membrane bioreactors are based on the separation of gas and liquid phase by a membrane. A
706 nutrient solution, containing the pollutant degrading microorganisms, is continuously
707 recirculated at one side of the membrane, while the contaminated air flows (usually counter-
708 currently) on the other side. An attached biofilm might be formed on the aqueous side of the
709 membrane. The pollutants diffuse from the gas side through the membrane and are biodegraded
710 by the microorganisms in the biofilm or in the bulk cultivation medium (Soreanu and Dumont,
711 2020). Despite exhibiting high investment costs, membrane bioreactors bring some innovations
712 in the field of indoor air purification. First, the air stream and microorganisms in liquid phase
713 are physically separated, which allows a better control of operational conditions, including
714 biofilm thickness and nutrient supply, and prevents the drying of the biofilm. Secondly, the risk
715 of an undesired stripping of microorganisms is avoided and the excess of humidity in the
716 purified air is limited. Finally, the mass-transfer of gas pollutants is improved due to the affinity
717 and permeability of the membrane, especially in the case of hydrophobic pollutants (Kumar et
718 al., 2008; Studer and von Rohr, 2008). Membrane bioreactors have been tested for the treatment
719 of high VOC concentration, and their performance in indoor air applications remains

720 unexplored. Promising removal efficiencies have been obtained by Lebrero et al. (2013; 2014),
721 although the degradation of highly hydrophobic pollutants like n-hexane is still problematic.
722 (Lebrero et al., 2014, 2013).
723 Capillary bioreactors are a new approach on the abatement of gas pollutants. Capillary
724 bioreactors are engineered as parallel straight microchannels, with a maximum internal
725 diameter of 5 mm in air-water reactors (Kreutzer et al., 2005b). A segmented flow (or Taylor
726 flow) is desired inside the capillaries, which consists of alternating sections of gas and liquid
727 (air bubbles and liquid slugs) that flow co-currently either upwards or downwards. The mass-
728 transfer of gas pollutants is enhanced by the internal circulation within liquid slugs, which
729 increases the contact between the gas and the liquid phase. This configuration improves the gas-
730 liquid mass-transfer (much higher than conventional stirred systems), while pressure drop
731 remains low (Kraakman et al., 2011; Kreutzer et al., 2005b, 2005a; Rocha-Rios et al., 2013).
732 This technology could achieve better results than traditional bioreactors for a given power input
733 (Kreutzer et al., 2005a). Although capillary bioreactors are promising solutions for indoor air
734 purification, some problems such as the long-term maintenance of a robust Taylor flow needs
735 to be solved (Kreutzer et al., 2005a). In this context, some innovative designs have been
736 proposed, such as a capillary microbioreactor where pollutants are pre-concentrated to
737 guarantee an excellent performance of the Taylor flow bioreactor, (López De León et al., 2019).
738 Microalgae fix $CO_2$ during photosynthesis using light as energy source while releasing $O_2$ to
739 the ambient air. While plants can also perform photosynthesis, algae are much more effective
740 in this process because of the simpler cell structure and higher light utilization efficiencies
741 (Brennan and Owende, 2010; Soreanu and Dumont, 2020). Algae photobioreactors may be a
742 feasible solution for indoor environments with elevated $CO_2$ levels such as offices, schools or
743 shopping centers. Some species of microalgae are also able to use hydrocarbons from the
744 environment to obtain carbon and energy (heterotrophic metabolism), and even exhibit a mixed
745 metabolism depending on the environmental conditions. Microalgae systems have been widely

746 studied in recent decades for biofuel or food production and wastewater treatment, where
747 operational conditions are far from those encountered in indoors environments (Anbalagan et
748 al., 2017; Mendoza et al., 2013; Niederwieser, 2015; Soreanu and Dumont, 2020). However,
749 there are few studies assessing the performance of algal photobioreactors as facades for indoor
750 air purification as well as energy recovery systems (Araji and Shahid, 2018; Wilkinson et al.,
751 2017).
752
753 **Conclusions**
754 The problem of exposure to indoor air pollution has become more apparent in recent years, as
755 people spend more than 80% of the time indoors and buildings are progressively sealed against
756 the environment to obtain heating and cooling energy savings. Recent studies have shown that
757 poor indoor air quality is a major contributor to global health problems and causes multi-
758 millionaire losses. Currently, there is not a single physical-chemical technology that can
759 efficiently address all challenges related to indoor air purification. Biological based purification
760 systems are promising solutions to overcome the limitations of indoor air treatment, such as
761 diversity and hydrophobicity of pollutants, variability of concentrations, etc. Additionally, these
762 systems need to assure humidity control of purified air, prevent microorganism releases and
763 incorporate $CO_2$ removal. The accomplishment of all these features would lead to 'green'
764 energy efficient systems able to improve IAQ. Some hybrid solutions integrating
765 biotechnologies with physical-chemical systems have been proposed to overcome these
766 limitations, where technologies complement each other to cover a wider range of action.
767 As modern building regulations are based on energy savings, which reduces air exchange and
768 increases the concentration of indoor pollutants, future research should focus on the progressive
769 development of bio-based systems. Hence, biotechnologies have the potential to successfully
770 deal with the problem of poor IAQ, although more investigation is necessary to develop cost-

771 effective systems that can be integrated in indoor spaces combining optimal performance with
772 acceptable aesthetics.
773

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778 **References**

779 Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., Elsarrag, E., 2016. Occupant
780 productivity and office indoor environment quality: A review of the literature. Build.
781 Environ. 105, 369–389. https://doi.org/10.1016/j.buildenv.2016.06.001
782 Anbalagan, A., Toledo-Cervantes, A., Posadas, E., Rojo, E.M., Lebrero, R., González-Sánchez,
783 A., Nehrenheim, E., Muñoz, R., 2017. Continuous photosynthetic abatement of CO2 and
784 volatile organic compounds from exhaust gas coupled to wastewater treatment: Evaluation
785 of tubular algal-bacterial photobioreactor. J. CO2 Util. 21, 353–359.
786 https://doi.org/10.1016/j.jcou.2017.07.016
787 ANSES, CSTB, OQAI, 2014. "Étude exploratoire du coût socio-économique des polluants de
788 l'air intérieur" (Rapport d'étude).
789 Araji, M.T., Shahid, I., 2018. Symbiosis optimization of building envelopes and micro-algae
790 photobioreactors. J. Build. Eng. 18, 58–65. https://doi.org/10.1016/j.jobe.2018.02.008
791 Armendáriz-Arnez, C., Edwards, R.D., Johnson, M., Rosas, I.A., Espinosa, F., Masera, O.R.,
792 2010. Indoor particle size distributions in homes with open fires and improved Patsari cook
793 stoves. Atmos. Environ. 44, 2881–2886. https://doi.org/10.1016/j.atmosenv.2010.04.049
794 ATSDR, 2007. Ethylbenzene- ToxFAQs™. 1–2.
795 Bak, A., Kozik, V., Dybal, P., Sulowicz, S., Kasperczyk, D., Kus, S., Barbusinski, K., 2017.
796 Abatement robustness of volatile organic compounds using compact trickle-bed
797 bioreactor: Biotreatment of styrene, ethanol and dimethyl sulfide mixture in contaminated
798 airstream. Int. Biodeterior. Biodegrad. 119, 316–328.
799 https://doi.org/10.1016/j.ibiod.2016.10.039
800 Barmparesos, N., Assimakopoulos, M.N., Assimakopoulos, V.D., Loumos, N., Sotiriou, M.A.,
801 Koukoumtzis, A., 2018. Indoor air quality and thermal conditions in a primary school with
802 a green roof system. Atmosphere (Basel). 9, 1–14. https://doi.org/10.3390/atmos9020075
803 Brennan, L., Owende, P., 2010. Biofuels from microalgae — A review of technologies for

804 production , processing , and extractions of biofuels and co-products 14, 557–577.
805 https://doi.org/10.1016/j.rser.2009.10.009
806 Broderick, Á., Byrne, M., Armstrong, S., Sheahan, J., Coggins, A.M., 2017. A pre and post
807 evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative
808 social housing. Build. Environ. 122, 126–133.
809 https://doi.org/10.1016/j.buildenv.2017.05.020
810 Burge, P.S., 2004. Sick building syndrome. Occup. Environ. Med. 61, 185–190.
811 https://doi.org/10.1136/oem.2003.008813
812 Campagnolo, D., Saraga, D.E., Cattaneo, A., Spinazzè, A., Mandin, C., Mabilia, R., Perreca,
813 E., Sakellaris, I., Canha, N., Mihucz, V.G., Szigeti, T., Ventura, G., Madureira, J., de
814 Oliveira Fernandes, E., de Kluizenaar, Y., Cornelissen, E., Hänninen, O., Carrer, P.,
815 Wolkoff, P., Cavallo, D.M., Bartzis, J.G., 2017. VOCs and aldehydes source identification
816 in European office buildings - The OFFICAIR study. Build. Environ. 115, 18–24.
817 https://doi.org/10.1016/j.buildenv.2017.01.009
818 Canha, N., Lage, J., Candeias, S., Alves, C., Almeida, S.M., 2017. Indoor air quality during
819 sleep under different ventilation patterns. Atmos. Pollut. Res. 8, 1132–1142.
820 https://doi.org/10.1016/j.apr.2017.05.004
821 Carazo Fernández, L., Fernández Alvarez, R., González-Barcala, F.J., Rodríguez Portal, J.A.,
822 2013. Indoor Air Contaminants and their Impact on Respiratory Pathologies. Arch.
823 Bronconeumol. 49, 22–27. https://doi.org/10.1016/j.arbr.2012.11.004
824 Chen, J., Zhang, D., Li, G., An, T., Fu, J., 2016. The health risk attenuation by simultaneous
825 elimination of atmospheric VOCs and POPs from an e-waste dismantling workshop by an
826 integrated de-dusting with decontamination technique. Chem. Eng. J. 301, 299–305.
827 https://doi.org/10.1016/j.cej.2016.05.013
828 Chen, W., Zhang, J.S., Zhang, Z., 2005. Performance of air cleaners for removing multiple
829 volatile organic compounds in indoor air. ASHRAE Trans. 111 PART 1, 1101–1114.

Chenari, B., Dias Carrilho, J., Gameiro Da Silva, M., 2016. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. Renew. Sustain. Energy Rev. 59, 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074

Cincinelli, A., Martellini, T., Amore, A., Dei, L., Marrazza, G., Carretti, E., Belosi, F., Ravegnani, F., Leva, P., 2016. Measurement of volatile organic compounds (VOCs) in libraries and archives in Florence (Italy). Sci. Total Environ. 572, 333–339. https://doi.org/10.1016/j.scitotenv.2016.07.201

Cros, C.J., Morrison, G.C., Siegel, J.A., Corsi, R.L., 2012. Long-term performance of passive materials for removal of ozone from indoor air. Indoor Air 22, 43–53. https://doi.org/10.1111/j.1600-0668.2011.00734.x

da Silva, C.F., Stefanowski, B., Maskell, D., Ormondroyd, G.A., Ansell, M.P., Dengel, A.C., Ball, R.J., 2017. Improvement of indoor air quality by MDF panels containing walnut shells. Build. Environ. 123, 427–436. https://doi.org/10.1016/j.buildenv.2017.07.015

Datta, A., Suresh, R., Gupta, A., Singh, D., Kulshrestha, P., 2017. Indoor air quality of non-residential urban buildings in Delhi, India. Int. J. Sustain. Built Environ. 6, 412–420. https://doi.org/10.1016/j.ijsbe.2017.07.005

De Robles, D., Kramer, S.W., 2017. Improving Indoor Air Quality through the Use of Ultraviolet Technology in Commercial Buildings. Procedia Eng. 196, 888–894. https://doi.org/10.1016/j.proeng.2017.08.021

Demeestere, K., Dewulf, J., De Witte, B., Beeldens, A., Van Langenhove, H., 2008. Heterogeneous photocatalytic removal of toluene from air on building materials enriched with TiO2. Build. Environ. 43, 406–414. https://doi.org/10.1016/j.buildenv.2007.01.016

Dodson, R.E., Levy, J.I., Spengler, J.D., Shine, J.P., Bennett, D.H., 2008. Influence of basements, garages, and common hallways on indoor residential volatile organic compound concentrations. Atmos. Environ. 42, 1569–1581. https://doi.org/10.1016/j.atmosenv.2007.10.088

856 Du, L., Batterman, S., Godwin, C., Rowe, Z., Chin, J.Y., Godwin, C., Rowe, Z., Chin, J.Y.,
857 2015. Air exchange rates and migration of VOCs in basements and residences. Indoor Air
858 25, 598–609. https://doi.org/10.1111/ina.12178
859 Edwards, R.D., Jurvelin, J., Saarela, K., Jantunen, M.J., 2001. VOC concentrations measured
860 in personal samples and residential indoor, outdoor and workplace microenvironments in
861 EXPOLIS-Helsinki, Finland. Atmos. Environ. 35, 4531–4543.
862 https://doi.org/10.1016/S1352-2310(01)00230-8
863 Estrada, J.M., Kraakman, N.J.R.B., Muñoz, R., Lebrero, R., 2011. A comparative analysis of
864 odour treatment technologies in wastewater treatment plants. Environ. Sci. Technol. 45,
865 1100–1106. https://doi.org/10.1021/es103478j
866 EU Council, 2008. COUNCIL DIRECTIVE 1976L0769.
867 European Comission, 2003. Indoor air pollution: new EU research reveals higher risks than
868 previously thought, European Comission.
869 European Environment Agency, 2017. Air quality in Europe — 2017 report.
870 https://doi.org/10.2800/850018
871 European Environment Agency, 2013. Air quality in Europe—2013 Report: EEA report no
872 9/2013, European Union. https://doi.org/10.2800/92843
873 European Environmental Agency, 2019. Air quality in Europe — 2019 report.
874 https://doi.org/10.2800/822355
875 European Parliament, 2010. DIRECTIVE 2010/31/EU, Official Journal of the European Union.
876 Feng, S., Li, D., Low, Z., Liu, Z., Zhong, Z., Hu, Y., Wang, Y., Xing, W., 2017. ALD-seeded
877 hydrothermally-grown Ag/ZnO nanorod PTFE membrane as efficient indoor air filter. J.
878 Memb. Sci. 531, 86–93. https://doi.org/10.1016/j.memsci.2017.02.042
879 Gall, E.T., Corsi, R.L., Siegel, J.A., 2011. Barriers and opportunities for passive removal of
880 indoor ozone. Atmos. Environ. 45, 3338–3341.
881 https://doi.org/10.1016/j.atmosenv.2011.03.032

882 Geiss, O., Giannopoulos, G., Tirendi, S., Barrero-Moreno, J., Larsen, B.R., Kotzias, D., 2011.
883 The AIRMEX study - VOC measurements in public buildings and schools/kindergartens
884 in eleven European cities: Statistical analysis of the data. Atmos. Environ. 45, 3676–3684.
885 https://doi.org/10.1016/j.atmosenv.2011.04.037
886 Guieysse, B., Hort, C., Platel, V., Munoz, R., Ondarts, M., Revah, S., 2008. Biological
887 treatment of indoor air for VOC removal: Potential and challenges. Biotechnol. Adv. 26,
888 398–410. https://doi.org/10.1016/j.biotechadv.2008.03.005
889 Guyot, G., Sherman, M.H., Walker, I.S., 2018. Smart ventilation energy and indoor air quality
890 performance in residential buildings: A review. Energy Build. 165, 416–430.
891 https://doi.org/10.1016/j.enbuild.2017.12.051
892 Harriman, L., Stephens, B., Brennan, T., 2019. New guidance for residential air cleaners.
893 ASHRAE J. 61, 14–23.
894 Héquet, V., Raillard, C., Debono, O., Thévenet, F., Locoge, N., Le Coq, L., 2018.
895 Photocatalytic oxidation of VOCs at ppb level using a closed-loop reactor: The mixture
896 effect. Appl. Catal. B Environ. 226, 473–486.
897 https://doi.org/10.1016/j.apcatb.2017.12.041
898 Hort, C., Platel, V., Sochard, S., Luengas Munoz, A.T., Ondarts, M., Reguer, A., Barona, A.,
899 Elias, A., 2014. A hybrid biological process of indoor air treatment for toluene removal. J.
900 Air Waste Manag. Assoc. 64, 1403–1409. https://doi.org/10.1080/10962247.2014.958622
901 Hubbard, H.F., Coleman, B.K., Sarwar, G., Corsi, R.L., 2005. Effects of an ozone-generating
902 air purifier on indoor secondary particles in three residential dwellings. Indoor Air 15,
903 432–444. https://doi.org/10.1111/j.1600-0668.2005.00388.x
904 INSHT, 2015. Guía técnica para la evaluación y prevención de los riesgos relativos a la
905 utilización de los lugares de tra? bajo, Boletín Oficial del Estado.
906 Jantunen, M., Oliveira, E.F., Carrer, P., Kephalopoulos, S., 2011. Promoting actions for healthy
907 indoor air (IAIAQ), European Commission Directorate General for Health and

908 Consumers. Luxembourg. https://doi.org/10.2772/61352
909 Jantunen, M.J., Katsouyanni, K., Knöppel, H., Kuenzli, N., Lebret, E., Maroni, M., Saarela, K.,
910 Srám, R., Zmirou, D., 1998. Air pollution exposure in European cities: The "EXPOLIS"
911 study.
912 Jo, W.K., Yang, C.H., 2009. Granular-activated carbon adsorption followed by annular-type
913 photocatalytic system for control of indoor aromatic compounds. Sep. Purif. Technol. 66,
914 438–442. https://doi.org/10.1016/j.seppur.2009.02.014
915 Kadribegovic, R., Ekberg, L., Gilligan, A., Shi, B., 2011. Air cleaning by photo catalytic
916 oxidation: An experimental performance test. ASHRAE Trans. 117, 426–433.
917 Kennes, C., Veiga, M.C., 2013. Air Pollution Prevention and Control Air Pollution Prevention
918 and Control Bioreactors and Bioenergy. https://doi.org/10.1002/9781118523360
919 Kim, K.J., Ahn, H.G., 2012. The effect of pore structure of zeolite on the adsorption of VOCs
920 and their desorption properties by microwave heating. Microporous Mesoporous Mater.
921 152, 78–83. https://doi.org/10.1016/j.micromeso.2011.11.051
922 Kotzias, D., Geiss, O., Tirendi, S., Josefa, B.M., Reina, V., Gotti, A., Cimino-Reale, G., Casati,
923 B., Marafante, E., Sarigiannis, D., 2009. Exposure to multiple air contaminants in public
924 buildings, schools and kindergartens-the European indoor air monitoring and exposure
925 assessment (AIRMEX) study. Fresenius Environ. Bull. 18, 670–681.
926 Kotzias, D., Koistinen, K., Kephalopoulos, S., Schlitt, C., Carrer, P., Maroni, M., Jantunen,
927 M.J., Cochet, C., Kirchner, S., Lindvall, T., Mclaughlin, J., Mølhave, L., de Oliveira
928 Fernandes, E., Seifert, B., 2005. The INDEX project. Critical Appraisal of the Setting and
929 Implementation of Indoor Exposure Limits in the EU. Ispra (Italy).
930 Kraakman, N.J.R., Rocha-Rios, J., Van Loosdrecht, M.C.M., 2011. Review of mass transfer
931 aspects for biological gas treatment. Appl. Microbiol. Biotechnol. 91, 873–886.
932 https://doi.org/10.1007/s00253-011-3365-5
933 Kreutzer, M.T., Kapteijn, F., Moulijn, J.A., Ebrahimi, S., Kleerebezem, R., Van Loosdrecht,

M.C.M., 2005a. Monoliths as biocatalytic reactors: Smart gas-liquid contacting for process intensification. Ind. Eng. Chem. Res. 44, 9646–9652. https://doi.org/10.1021/ie050286m

Kreutzer, M.T., Kapteijn, F., Moulijn, J.A., Heiszwolf, J.J., 2005b. Multiphase monolith reactors: Chemical reaction engineering of segmented flow in microchannels. Chem. Eng. Sci. 60, 5895–5916. https://doi.org/10.1016/j.ces.2005.03.022

Kumar, A., Dewulf, J., Van Langenhove, H., 2008. Membrane-based biological waste gas treatment. Chem. Eng. J. 136, 82–91. https://doi.org/10.1016/j.cej.2007.06.006

Kumar, P., Martani, C., Morawska, L., Norford, L., Choudhary, R., Bell, M., Leach, M., 2016. Indoor air quality and energy management through real-time sensing in commercial buildings. Energy Build. 111, 145–153. https://doi.org/10.1016/j.enbuild.2015.11.037

Langer, S., Bekö, G., Bloom, E., Widheden, A., Ekberg, L., 2015. Indoor air quality in passive and conventional new houses in Sweden. Build. Environ. 93, 92–100. https://doi.org/10.1016/j.buildenv.2015.02.004

Lebrero, R., Gondim, A.C., Pérez, R., García-Encina, P.A., Muñoz, R., 2014. Comparative assessment of a biofilter, a biotrickling filter and a hollow fiber membrane bioreactor for odor treatment in wastewater treatment plants. Water Res. 49, 339–350. https://doi.org/10.1016/j.watres.2013.09.055

Lebrero, R., Rodríguez, E., García-Encina, P.A., Muñoz, R., 2011. A comparative assessment of biofiltration and activated sludge diffusion for odour abatement. J. Hazard. Mater. 190, 622–630. https://doi.org/10.1016/j.jhazmat.2011.03.090

Lebrero, R., Volckaert, D., Pérez, R., Muñoz, R., Van Langenhove, H., 2013. A membrane bioreactor for the simultaneous treatment of acetone, toluene, limonene and hexane at trace level concentrations. Water Res. 47, 2199–2212. https://doi.org/10.1016/j.watres.2013.01.041

Leung, D.Y.C., 2015. Outdoor-indoor air pollution in urban environment: Challenges and opportunity. Front. Environ. Sci. 2, 1–7. https://doi.org/10.3389/fenvs.2014.00069

960 Liang, Y., Wu, Y., Sun, K., Chen, Q., Shen, F., Zhang, J., Yao, M., Zhu, T., Fang, J., 2012.
961 Rapid inactivation of biological species in the air using atmospheric pressure nonthermal
962 plasma. Environ. Sci. Technol. 46, 3360–3368. https://doi.org/10.1021/es203770q
963 Liu, Y.J., Mu, Y.J., Zhu, Y.G., Ding, H., Crystal Arens, N., 2007. Which ornamental plant
964 species effectively remove benzene from indoor air? Atmos. Environ. 41, 650–654.
965 https://doi.org/10.1016/j.atmosenv.2006.08.001
966 López De León, L.R., Deaton, K.E., Deshusses, M.A., 2019. Miniaturized Biotrickling Filters
967 and Capillary Microbioreactors for Process Intensification of VOC Treatment with
968 Intended Application to Indoor Air. Environ. Sci. Technol. 53, 1518–1526.
969 https://doi.org/10.1021/acs.est.8b05209
970 Lu, N., Pei, J., Zhao, Y., Qi, R., Liu, J., 2012. Performance of a biological degradation method
971 for indoor formaldehyde removal. Build. Environ. 57, 253–258.
972 https://doi.org/10.1016/j.buildenv.2012.05.007
973 Luengas, A., Barona, A., Hort, C., Gallastegui, G., Platel, V., Elias, A., 2015. A review of
974 indoor air treatment technologies. Rev. Environ. Sci. Biotechnol. 14, 499–522.
975 https://doi.org/10.1007/s11157-015-9363-9
976 Luengas, A.T., Hort, C., Platel, V., Elias, A., Barona, A., Moynault, L., 2017. Removal of traces
977 of toluene and p-xylene in indoor air using biofiltration and a hybrid system (biofiltration
978 + adsorption). Environ. Sci. Pollut. Res. 24, 10674–10684.
979 https://doi.org/10.1007/s11356-017-8689-y
980 Mandin, C., Trantallidi, M., Cattaneo, A., Canha, N., Mihucz, V.G., Szigeti, T., Mabilia, R.,
981 Perreca, E., Spinazzè, A., Fossati, S., De Kluizenaar, Y., Cornelissen, E., Sakellaris, I.,
982 Saraga, D., Hänninen, O., De Oliveira Fernandes, E., Ventura, G., Wolkoff, P., Carrer, P.,
983 Bartzis, J., 2017. Assessment of indoor air quality in office buildings across Europe – The
984 OFFICAIR study. Sci. Total Environ. 579, 169–178.
985 https://doi.org/10.1016/j.scitotenv.2016.10.238

986 Marć, M., Śmiełowska, M., Namieśnik, J., Zabiegała, B., 2018. Indoor air quality of everyday
987 use spaces dedicated to specific purposes—a review. Environ. Sci. Pollut. Res. 25, 2065–
988 2082. https://doi.org/10.1007/s11356-017-0839-8
989 Mendoza, J.L., Granados, M.R., de Godos, I., Acién, F.G., Molina, E., Heaven, S., Banks, C.J.,
990 2013. Oxygen transfer and evolution in microalgal culture in open raceways. Bioresour.
991 Technol. 137, 188–195. https://doi.org/10.1016/j.biortech.2013.03.127
992 Mo, J., Zhang, Y., Xu, Q., Lamson, J.J., Zhao, R., 2009. Photocatalytic purification of volatile
993 organic compounds in indoor air: A literature review. Atmos. Environ. 43, 2229–2246.
994 https://doi.org/10.1016/j.atmosenv.2009.01.034
995 Moya, T.A., van den Dobbelsteen, A., Ottelé, M., Bluyssen, P.M., 2019. A review of green
996 systems within the indoor environment. Indoor Built Environ. 28, 298–309.
997 https://doi.org/10.1177/1420326X18783042
998 Muñoz, R., Daugulis, A.J., Hernández, M., Quijano, G., 2012. Recent advances in two-phase
999 partitioning bioreactors for the treatment of volatile organic compounds. Biotechnol. Adv.
1000 30, 1707–1720. https://doi.org/10.1016/j.biotechadv.2012.08.009
1001 Niederwieser, T., 2015. Evaluation of a flow-through test bed for algal atmosphere
1002 revitalization in spaceflight applications. Aerosp. Eng. Sci. Grad. Theses Diss. 139.
1003 Oh, G.S., Jung, G.J., Seo, M.H., Im, Y. Bin, 2011. Experimental study on variations of CO2
1004 concentration in the presence of indoor plants and respiration of experimental animals.
1005 Hortic. Environ. Biotechnol. 52, 321–329. https://doi.org/10.1007/s13580-011-0169-6
1006 Pacheco-Torgal, F., Labrincha, J.A., Diamanti, M. V., Yu, C.P., Lee, H.K., 2015.
1007 Biotechnologies and biomimetics for civil engineering, Biotechnologies and Biomimetics
1008 for Civil Engineering. https://doi.org/10.1007/978-3-319-09287-4
1009 Pokhrel, A.K., Bates, M.N., Acharya, J., Valentiner-branth, P., Chandyo, R.K., Shrestha, P.S.,
1010 Raut, A.K., Smith, K.R., 2015. PM 2.5 in household kitchens of Bhaktapur, Nepal, using
1011 four different cooking fuels. Atmos. Environ. 113, 159–168.

https://doi.org/10.1016/j.atmosenv.2015.04.060

Polidori, A., Fine, P.M., White, V., Kwon, P.S., 2013. Pilot study of high-performance air filtration for classroom applications. Indoor Air 23, 185–195. https://doi.org/10.1111/ina.12013

Prasauskas, T., Martuzevicius, D., Kalamees, T., Kuusk, K., Leivo, V., Haverinen-Shaughnessy, U., 2016. Effects of Energy Retrofits on Indoor Air Quality in Three Northern European Countries. Energy Procedia 96, 253–259. https://doi.org/10.1016/j.egypro.2016.09.134

Rocha-Rios, J., Kraakman, N.J.R., Kleerebezem, R., Revah, S., Kreutzer, M.T., van Loosdrecht, M.C.M., 2013. A capillary bioreactor to increase methane transfer and oxidation through Taylor flow formation and transfer vector addition. Chem. Eng. J. 217, 91–98. https://doi.org/10.1016/j.cej.2012.11.065

Rösch, C., Kohajda, T., Röder, S., von Bergen, M., Schlink, U., 2014. Relationship between sources and patterns of VOCs in indoor air. Atmos. Pollut. Res. 5, 129–137. https://doi.org/10.5094/APR.2014.016

Roso, M., Falcomer, D., Azzano, A., Boaretti, C., Donadini, R., Lorenzetti, A., Modesti, M., 2019. Design and development of nanostructured filter media for VOCs abatement in closed environments. J. Environ. Chem. Eng. 7, 103045. https://doi.org/10.1016/j.jece.2019.103045

Royal College of Physicians, 2016. Every breath we take: the lifelong impact of air pollution. Report of a working party. London.

Satish, U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., Fisk, W.J., 2012. Concentrations on Human Decision-Making Performance. Environ. Health Perspect. 120, 1671–1678. https://doi.org/10.1289/ehp.1104789

Saucedo-Lucero, J.O., Revah, S., 2018. Monitoring key organic indoor pollutants and their elimination in a biotrickling biofilter. Environ. Sci. Pollut. Res. 25, 9806–9816.

https://doi.org/10.1007/s11356-018-1274-1

SCHER, 2007. Opinion on risk assessment on indoor air quality.

Sidhu, M.K., Ravindra, K., Mor, S., John, S., 2017. Household air pollution from various types of rural kitchens and its exposure assessment. Sci. Total Environ. 586, 419–429. https://doi.org/10.1016/j.scitotenv.2017.01.051

Singh, D., Kumar, A., Kumar, K., Singh, B., Mina, U., Singh, B.B., Jain, V.K., 2016. Statistical modeling of O3, NOx, CO, PM2.5, VOCs and noise levels in commercial complex and associated health risk assessment in an academic institution. Sci. Total Environ. 572, 586–594. https://doi.org/10.1016/j.scitotenv.2016.08.086

Soreanu, G., 2016. Biotechnologies for improving indoor air quality, in: Start-Up Creation: The Smart Eco-Efficient Built Environment. Elsevier Ltd, pp. 301–328. https://doi.org/10.1016/B978-0-08-100546-0.00012-1

Soreanu, G., Dumont, É., 2020. From Biofiltration to Promising Options in Gaseous Fluxes Biotreatment. Recent Developments, New Trends, Advances, and Opportunities. https://doi.org/10.1016/c2018-0-03712-3

Srivastava, I., Singh, P.K., Gupta, T., Sankararamakrishnan, N., 2019. Preparation of mesoporous carbon composites and its highly enhanced removal capacity of toxic pollutants from air. J. Environ. Chem. Eng. 7, 103271. https://doi.org/10.1016/j.jece.2019.103271

Studer, M., von Rohr, R., 2008. Novel Membrane Bioreactor: Able to Cope With Fluctuating Loads, Poorly Water Soluble VOCs, and Biomass Accumulation. Biotechnol. Bioeng. 99, 38–48. https://doi.org/10.1002/bit.21532

Sung, J.H., Kim, M., Kim, Y.J., Han, B., Hong, K.J., Kim, H.J., 2019. Ultrafine particle cleaning performance of an ion spray electrostatic air cleaner emitting zero ozone with diffusion charging by carbon fiber. Build. Environ. 166, 106422. https://doi.org/10.1016/j.buildenv.2019.106422

1064 Tang, X., Wei, J., Kong, Z., Zhang, H., Tian, J., 2020. Introduction of amino and rGO into PP
1065 nonwoven surface for removal of gaseous aromatic pollutants and particulate matter from
1066 air. Appl. Surf. Sci. 511, 145631. https://doi.org/10.1016/j.apsusc.2020.145631
1067 Torpy, F., Clements, N., Pollinger, M., Dengel, A., Mulvihill, I., He, C., Irga, P., 2018. Testing
1068 the single-pass VOC removal efficiency of an active green wall using methyl ethyl ketone
1069 (MEK). Air Qual. Atmos. Heal. 11, 163–170. https://doi.org/10.1007/s11869-017-0518-4
1070 Torpy, F.R., Irga, P.J., Burchett, M.D., 2014. Profiling indoor plants for the amelioration of
1071 high CO2 concentrations. Urban For. Urban Green. 13, 227–233.
1072 https://doi.org/10.1016/j.ufug.2013.12.004
1073 Tran, T.V., Dang, N.T., Chung, W.Y., 2017. Battery-free smart-sensor system for real-time
1074 indoor air quality monitoring. Sensors Actuators, B Chem. 248, 930–939.
1075 https://doi.org/10.1016/j.snb.2017.01.198
1076 US Environmental Protection Agency, 1995. The Inside Story : A Guide to Indoor Air Quality.
1077 EPA Doc. # 402-K-93-007.
1078 Van Durme, J., Dewulf, J., Demeestere, K., Leys, C., Van Langenhove, H., 2009. Post-plasma
1079 catalytic technology for the removal of toluene from indoor air: Effect of humidity. Appl.
1080 Catal. B Environ. 87, 78–83. https://doi.org/10.1016/j.apcatb.2008.08.015
1081 Van Groenestijn, J.W., Kraakman, N.J.R., 2005. Recent developments in biological waste gas
1082 purification in Europe. Chem. Eng. J. 113, 85–91.
1083 https://doi.org/10.1016/j.cej.2005.03.007
1084 Vasile, V., Petran, H., Dima, A., Petcu, C., 2016. Indoor Air Quality - A Key Element of the
1085 Energy Performance of the Buildings. Energy Procedia 96, 277–284.
1086 https://doi.org/10.1016/j.egypro.2016.09.150
1087 Verma, V.K., Subbiah, S., Kota, S.H., 2019. Sericin-coated polyester based air-filter for
1088 removal of particulate matter and volatile organic compounds (BTEX) from indoor air.
1089 Chemosphere 237, 124462. https://doi.org/10.1016/j.chemosphere.2019.124462

1090 Wang, N., Raza, A., Si, Y., Yu, J., Sun, G., Ding, B., 2013. Tortuously structured polyvinyl
1091 chloride/polyurethane fibrous membranes for high-efficiency fine particulate filtration. J.
1092 Colloid Interface Sci. 398, 240–246. https://doi.org/10.1016/j.jcis.2013.02.019
1093 Wang, Z., Pei, J., Zhang, J.S., 2014. Experimental investigation of the formaldehyde removal
1094 mechanisms in a dynamic botanical filtration system for indoor air purification. J. Hazard.
1095 Mater. 280, 235–243. https://doi.org/10.1016/j.jhazmat.2014.07.059
1096 Wei, W., Ramalho, O., Mandin, C., 2015. Indoor air quality requirements in green building
1097 certifications. Build. Environ. 92, 10–19. https://doi.org/10.1016/j.buildenv.2015.03.035
1098 WHO Regional Office for Europe, 2015. Economic cost of the health impact of air pollution in
1099 Europe: Clean air, health and wealth.
1100 Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L.N., Kuzava, G.S., 2017. Exploring
1101 the Feasibility of Algae Building Technology in NSW. Procedia Eng. 180, 1121–1130.
1102 https://doi.org/10.1016/j.proeng.2017.04.272
1103 Wood, R.A., Burchett, M.D., Alquezar, R., Orwell, R.L., Tarran, J., Torpy, F., 2006. The
1104 potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-
1105 study. Water. Air. Soil Pollut. 175, 163–180. https://doi.org/10.1007/s11270-006-9124-z
1106 World Bank, Institute for Health Metrics and Evaluation, 2016. The Cost of Air Pollution:
1107 Strengthening the Economic Case for Action. Washington, DC.
1108 World Health Organization, 2016. Ambient Air Pollution: A global assessment of exposure and
1109 burden of disease.
1110 World Health Organization, 2014. Burden of disease from Household Air Pollution for 2012.
1111 World Health Organization, WHO Regional Office for Europe, 2010. WHO guidelines for
1112 indoor air quality: selected pollutants.
1113 Xu, J., Szyszkowicz, M., Jovic, B., Cakmak, S., Austin, C.C., Zhu, J., 2016. Estimation of
1114 indoor and outdoor ratios of selected volatile organic compounds in Canada. Atmos.
1115 Environ. 141, 523–531. https://doi.org/10.1016/j.atmosenv.2016.07.031

1116 Xu, Z., Yu, J., Xiao, W., 2013. Microemulsion-assisted preparation of a mesoporous
1117 ferrihydrite/SiO 2 composite for the efficient removal of formaldehyde from air. Chem. -
1118 A Eur. J. 19, 9592–9598. https://doi.org/10.1002/chem.201300438
1119 Yamamoto, S.S., Louis, V.R., Sié, A., Sauerborn, R., 2014. Biomass smoke in Burkina Faso:
1120 What is the relationship between particulate matter, carbon monoxide, and kitchen
1121 characteristics? Environ. Sci. Pollut. Res. 21, 2581–2591. https://doi.org/10.1007/s11356-
1122 013-2062-6
1123 Yang, C.T., Chen, S.T., Den, W., Wang, Y.T., Kristiani, E., 2019. Implementation of an
1124 Intelligent Indoor Environmental Monitoring and management system in cloud. Futur.
1125 Gener. Comput. Syst. 96, 731–749. https://doi.org/10.1016/j.future.2018.02.041
1126 Yang, D.S., Pennisi, S. V., Son, K.C., Kays, S.J., 2009. Screening indoor plants for volatile
1127 organic pollutant removal efficiency. HortScience 44, 1377–1381.
1128 https://doi.org/10.21273/hortsci.44.5.1377
1129 Yip, F., Christensen, B., Sircar, K., Naeher, L., Bruce, N., Pennise, D., Lozier, M., Pilishvili,
1130 T., Loo Farrar, J., Stanistreet, D., Nyagol, R., Muoki, J., de Beer, L., Sage, M., Kapil, V.,
1131 2017. Assessment of traditional and improved stove use on household air pollution and
1132 personal exposures in rural western Kenya. Environ. Int. 99, 185–191.
1133 https://doi.org/10.1016/j.envint.2016.11.015
1134 Zadi, T., Azizi, M., Nasrallah, N., Bouzaza, A., Maachi, R., Wolbert, D., Rtimi, S., Assadi,
1135 A.A., 2020. Indoor air treatment of refrigerated food chambers with synergetic association
1136 between cold plasma and photocatalysis: Process performance and photocatalytic
1137 poisoning. Chem. Eng. J. 382, 122951. https://doi.org/10.1016/j.cej.2019.122951
1138 Zeng, Y., Xie, R., Cao, J., Chen, Z., Fan, Q., Liu, B., Lian, X., Huang, H., 2020. Simultaneous
1139 removal of multiple indoor-air pollutants using a combined process of electrostatic
1140 precipitation and catalytic decomposition. Chem. Eng. J. 388, 124219.
1141 https://doi.org/10.1016/j.cej.2020.124219

Zhang, J., Hu, Y., Qin, J., Yang, Z., Fu, M., 2020. TiO2-UiO-66-NH2 nanocomposites as efficient photocatalysts for the oxidation of VOCs. Chem. Eng. J. 385, 123814. https://doi.org/10.1016/j.cej.2019.123814

Zhong, L., Su, F.C., Batterman, S., 2017. Volatile organic compounds (VOCs) in conventional and high performance school buildings in the U.S. Int. J. Environ. Res. Public Health 14, 100. https://doi.org/10.3390/ijerph14010100

Zhou, C., Zhan, Y., Chen, S., Xia, M., Ronda, C., Sun, M., Chen, H., Shen, X., 2017. Combined effects of temperature and humidity on indoor VOCs pollution : Intercity comparison. Build. Environ. 121, 26–34. https://doi.org/10.1016/j.buildenv.2017.04.013

Zhu, Q., Tang, X., Feng, S., Zhong, Z., Yao, J., Yao, Z., 2019. ZIF-8@SiO2 composite nanofiber membrane with bioinspired spider web-like structure for efficient air pollution control. J. Memb. Sci. 581, 252–261. https://doi.org/10.1016/j.memsci.2019.03.075

Zielinska, B., Fujita, E., Ollison, W., Campbell, D., Sagebiel, J., Merritt, P., Smith, L., 2012. Relationships of attached garage and home exposures to fuel type and emission levels of garage sources. Air Qual. Atmos. Heal. 5, 89–100. https://doi.org/10.1007/s11869-010-0121-4

Zuraimi, M.S., Magee, R.J., Won, D.Y., Nong, G., Arsenault, C.D., Yang, W., So, S., Nilsson, G., Abebe, L., Alliston, C., 2018. Performance of sorption- and photocatalytic oxidation-based indoor passive panel technologies. Build. Environ. 135, 85–93. https://doi.org/10.1016/j.buildenv.2018.03.004