The positive effects of indoor plants on human wellbeing, productivity and mental health have been reported in several studies (Lohr et al., 1996, Kim et al., 2010a,b). Furthermore, a well-known fact is that the plants can also effectively improve the indoor air quality in term of reducing CO\textsubscript{2} and releasing O\textsubscript{2} through light-dependent process of photosynthesis and increase air humidity by water vapor transpired from leaves through microscopic leaf pores, namely “stomata”. Precisely the ability of leaves to exchange gases and, thus, to take up different pollutants from indoor air (e.g. VOCs, ammonia, ozone, particulate matter) makes the plants a cost effective and sustainable technique to ameliorate indoor air quality.

Since the pioneer studies conducted by NASA during the 1980s where was successfully demonstrated that plants are able to remove airborne pollutants (Wolverton et al., 1984), numerous of experiments aiming to understand the mechanisms and assess the efficiency of air phytoremediation (the use of plants to remove airborne pollutants) of different plant species have been published in the scientific literature (Godish et al., 1989; Wolverton et al., 1996; Liu et al., 2007; Aydogan et al., 2011, Abbass et al., 2017). An overview of a short literature review of the available recently published studies focused on the effectiveness of indoor plants to remove airborne pollutants from indoor air is shown in Table 1.

A large part of the studies is focused onto the air phytoremediation of VOCs. In fact, for the last 25 years more than 40 different studies, by 10 different research groups have tested approximately 200 species for VOC removal capacity, primarily focused in testing of the most well-known air polluting species such as benzene, ethylbenzene, xylene and toluene (BTEX), formaldehyde and trichloroethylene (Irga et al., 2018). Most of the studies reported high (above 65%) phytoremediation efficiency for various VOCs of the most commonly used indoor plans. For example, in the most recently published study of Teiri et al. (2018), the authors reported formaldehyde removal efficiency of 65-100% with maximum elimination capacity of 1.47 mg/h for a m\textsuperscript{2} of leaf area, during 48h exposure, by the very commonly used indoor parlour palm (Chamaedorea elegans). Moreover, the study also found that formaldehyde concentrations up to 14.6 mg/m\textsuperscript{3} did not show any effect to the plant growth. Similar results were published by Aydogan et al. (2011), where the formaldehyde removal efficiency of about 90% for 24h period was determined for other four indoor plant species (Hedera helix (English ivy), Chrysanthemum morifolium (pot mum), Dieffenbachia compacta (dump cane) and Epipremnum aureum (golden pathos)). In a study evaluating the effects that the presence of plants in classrooms might have onto
the pupils and the indoor air quality, performed in various classrooms in Netherlands by
the Netherlands Organisation for Applied Scientific Research (TNO) and a research
company of applied plant sciences (Pythagoras) reported formaldehyde elimination rate of
20 mg per hour for 5000 g of leaf mass using Spathiphyllum in a controlled test conditions
in a phytotron (Duijn et al., 2011). The authors also reported that the formaldehyde
removal ability of the tested specimens was not dependent from the applied photosynthyc
active light radiation (PAR) and remains present even at 0 PAR (i.e. dark conditions). In
term of benzene, toluene, ethylbenzene and xylene (BTEX) a study published by Sriprapat
et al. (2013) showed that Zamioculcas zamiifolia has a high potential of removing all four
compounds from indoor air for a long-time exposure. The study also showed the tested
plant was able to lower the concentration of BTEX in contaminated air from about 20 to 0
ppm within 12 days for benzene, 13 days for toluene, and 14 days for ethylbenzene and
xylene, respectively. The authors suggested that the different diffusion rates of the
gaseous pollutants are a rate-limiting process during phytoremediation. Similar results
were observed during another study, where uptake of toluene and ethylbenzene have
been examined for twelve plant species (Sriprapat et al., 2013). The removal efficiency of
toluene was averaged at about 77%, while the ethylbenzene removal efficiency was
averaged at about 70% across all examined species for 72h of exposure. High benzene
removal efficiency (91% - 97%) have been reported by Parseh et al. (2018), where two
plant species (Schefflera arboricola and Spathiphyllum wallisii) were exposed to benzene
containing atmosphere at concentrations between 3.6 – 29.5 µg/m³.

In term of ozone removal, a study published by Abbass et al. (2017) showed that the five-
tested species of the most commonly used indoor plants have moderate (0.9 – 9%) ozone
removal efficiency. Moreover, the authors also observed that the ozone removal efficiency
decreased in subsequent exposures. This suggested that ozone has affected the structure
or composition of the leaf surface, which leaded to reduction of in ozone removal activity.
Such structural changes of the plant leaves due to ozone exposure have been reported also
in other studies (Kozlowski, 1980; Lambers et al., 2008).

With respect of particulate matter (PM), while the ability for phytoremediation of the
aerosolised PM by outdoor plants is well established (Sæbø et al., 2012), little data exists
on PM phytoremediation from indoor air. The study by Stapleton et al. (2018) assessed the
effectiveness of plant species to reduce ultrafine particle concentrations in simulation
chambers. Most of the tested species were capable of ultrafine particle reduction with
maximum reduction of 19.9% (Juniper plants). The overall household ultrafine particle
reduction was estimated to be 11% using juniper plants. Moreover, the study also showed
strong correlation between the plant surface and the ultrafine particle reduction. Similar
results were reported by Gawrońska et al. (2015), where the ability of plants to take up
indoor PM was statistically significant. Further, their results also demonstrated that the
plants were capable of accumulating significantly more PM than flat surfaces within the
indoor environment, indicating that more than simple gravitational forces were involved in
PM accumulation on aerial plant parts.

Many of these experiments, however, have been the subject of criticism in term of
translating the findings to the real indoor environments. For instance, most of these
studies utilize small scale (<1m³) in vitro chamber system, constraining the generalisation
of the results to building scale settings (Torpy et al., 2018). In contrast with the small-scale chambers, buildings are much more complex systems with more dynamic air exchange with the exterior and varying rates of indoor pollutants (e.g. VOCs, PM). Moreover, the chamber-to-room volume ratios typically utilized in most experiments would be too small to be representative of in situ functional pollutant removal, due to the kinetic of this removal from such small atmospheric volumes relative to the size of the air cleaning system. For example, a study by Kim et al. (2009) the authors found that the VOC removal rate of a phytoremediation experiment in a sealed 60m³ room is 1/20th of that measured in a 1m³ chamber under otherwise identical conditions. Moreover, when the plans were tested in actual office environments (rooms with interior volumes of 275 and 350 m³, containing 16 to 19 occupants and 22 to 25 plants per office), no reduction was found in benzene, toluene, ethylene, or xylene concentrations (Kim et al., 2011). Additionally, the initial VOC concentrations to which the plants were exposed are substantially higher than is relevant to in situ levels (chamber-based VOC concentrations are usually tested in ppm range, while typically indoor VOC concentrations are in ppb range (Torpy et al., 2018)). Nevertheless, the static chamber tests might be useful in obtaining qualitative information regarding the efficiency of a system to reduce air pollutant concentrations, but they cannot provide information on their quantitative efficiency in in situ environments (Irga et al., 2018).

Despite of the strong empirical proof-of-concept provided by several studies, to what extent the indoor plants really have an impact on IAQ is still under debate (Thomas et al., 2015; Waring, 2016). Unaddressed challenges exist for the practical use of potted plants to create meaningful air quality effect. The few existing in situ studies reveal inconsistencies in air quality improvement (Llewellyn and Dixon, 2011). The most recently published study of Cummings and Waring (2019) showed that the VOC removal ability of the potted plants is orders of magnitude lower than the removal rate already provided by the outdoor-to-indoor exchange in typical building (~1/h). Similarly, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) and the French Environment & Energy Management Agency (ADEME) suggested ventilation and aeration as more efficient methods for remediation of indoor air pollutions than the phytoremediation by plants, because of the low efficiency and wide variety of influencing environment parameters of indoor air purification using plants (Ademe, 2011; Anses, 2017).
Table 1 Overview of recent scientific literature of effectiveness of indoor plants to remove airborne pollutants

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<th>Results</th>
<th>Conclusion</th>
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<td>Cummings and Waring (2019)</td>
<td>The study aimed to assess the potential impact on the indoor VOC loads by the potted plants. To achieve this the authors reviewed 12 published studies of performed chamber experiments on VOC reduction by various potted plant species. To be able to compare the impact, the 198 results from the reviewed studies were translated to clean air delivery rates (CADR, m³/h). The CADR is described as a clean air metric that can be normalized by volume to parametrize first-order loss indoors.</td>
<td>The results showed nearly four orders of magnitude spanning of the obtained CADR for potted plants, with a median value of 0.023 m³/h and mean 0.062 ± 0.089 m³/h per plant (ranging from 0.0004 to 0.2 m³/h per plant). The results suggested that a placement of 10 – 1000 plants/m² of a building’s floor space is necessary for the combined VOC removing ability by potted plants to achieve the same removal rate that outdoor-to-indoor air exchange already provides in typical buildings (~1/h)</td>
<td>The authors concluded that future experiments should be focused to the VOC uptake mechanisms, alternative biofiltration technologies, biophilic productivity and well-being benefits or negative impacts of other plant-sourced emissions instead of the potted plants’ (in)abilities to passively clean indoor air.</td>
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<td>Teiri et al. (2018)</td>
<td>The study investigated the ability of potted plant (Chamaedorea elegans) in formaldehyde removal from indoor air. The investigation was performed inside a chamber under controlled environment, where different concentrations of formaldehyde (0.66 - 16.4 mg/m³) were continuously introduced.</td>
<td>The results of the study showed that the plant efficiently removed formaldehyde from polluted air by 65 - 100%, depending of the inlet concentrations, for a long-time exposure. A maximum elimination capacity of 1.47 mg/m².h was achieved with an inlet formaldehyde concentration of 14.6 mg/m³. However, a noticeable decrease of the removal efficiency was observed for concentrations higher than 12 mg/m³, suggesting that the plant removal capacity was fillet. The entire plant showed more removal in day time rather than night time and darkness. The removal ratio of areal part to pot</td>
<td>From the results obtained during this study, the authors concluded that phytoremediation can be one of the most effective, economically and environmentally friendly indoor air purification methods.</td>
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soil and roots was found to be 2.45:1 (71%; 29%). The removal of formaldehyde from the soil and roots the authors attributed to the pollutant adsorption and metabolism by the microorganisms in the soil. The study examined the phytoremediation of benzene from polluted air by two plant species (*Schefflera arboricola* and *Spathiphyllum wallisii*). The experiments were performed in a Plexiglas chamber (84 cm x 62 cm x 72 cm) maintaining constant inside temperature of 21±3°C and relative humidity of 81±6%. A natural light source with a dark-light cycle of 12h were used during the experiment. The benzene removal efficiency was tested for a period of 36 days at various inlet concentrations in the range of 3.5-29.5 µg/m³. The average removal efficiency at various inlet concentrations including 3.5-6.5, 10.5-16.3, and 25-30 µg/m³ were reported to be 97%, 94% and 91%, respectively. The results showed that *Schefflera arboricola* and *Spathiphyllum wallisii*, as ornamental plants, have a good potential for benzene removal from indoor air.

**Parseh et al. (2018)**

The study assesses the effectiveness of plants to decrease ultrafine particle concentrations in indoor environments. Ambient ultrafine particle concentrations were measured for three hours in and outside a polycarbonate chamber with and without plants using a condensation particle counter. Reduction in ambient ultrafine particle levels between blanks and treatments of the tested plant species were compared using infiltration factors (Finfs). *Juniperus chinensis* 'San Jose' showed the highest per-plant ultrafine particle reduction (5.5%), while *Dracaena deremensis compacta* showed almost no ultrafine particle reduction. A linear relationship between number of within-chamber plants and percent ultrafine particle reduction was found ($r^2 = 0.95$) for juniper plants, the maximum achieved Finp reduction was 19.9%. Plant surface area was associated with ultrafine particle reduction ($r^2 = 0.85$) when comparing statistically significant results. The results from this study indicate that plants may provide a small, yet statistically significant ultrafine particle reduction in homes with the co-benefit of greening the indoor environment.

**Stapleton et al. (2018)**
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<td>Abbass et al. (2017)</td>
<td>The study determined ozone deposition velocities for five common indoor plants Peace Lily, Ficus, Calathia, Dieffenbachia, Golden Pothos during their exposure to ozonated air stream with concentration of 60±1.2 ppb in a glass chamber. During the tests, each specimen was exposed to 8h of ozonated air followed by 16h of non-ozonated stream.</td>
<td>The ozone deposition velocities of the tested plants were ranging from 0.5 to 5.5 m/h. The ozone removal effectiveness of the tested plant species was calculated as a function of the ratio of plant leaf area to volume of typical indoor environment at 0.9 - 9%.</td>
<td>The tested plant has shown moderate ozone deposition velocity and modest contribution to indoor ozone removal effectiveness for reasonable indoor loading factors of plant leaf surface area. The study also showed that the ozone possibly changes the composition or structure of the leaf surface lowering its removal ozone effectiveness of these species.</td>
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<td>Gawrońska et al. (2015)</td>
<td>The study investigates the ability of spider plants (Chlorophytum comosum L.) to take up particulate matter (PM) in the indoor air of five rooms housing different activities (a dental clinic, a perfume-bottling room, a suburban house, an apartment and an office).</td>
<td>The total amount of PM accumulated on the leaves of the spider plant differed between the rooms examined and ranged from 13.62 to 19.79 µg/cm², with the largest and smallest amounts recorded for the office and the suburban house, respectively. The amount of PM accumulated on the leaves were significantly higher in comparison with the amount deposited on aluminium plates, suggesting that the accumulation of the PM on leaves involves factors/forces other than gravitation.</td>
<td>Spider plants (Chlorophytum comosum L.) grown indoors accumulate particulate matter of both categories and all size fractions, irrespective of their location and the type of activity taking place in the examined room. They therefore phytoremediate PM from indoor air. The fine PM is accumulated to greater extend in the cuticles of the leaves.</td>
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<td>Sriprapat et al. (2014)</td>
<td>The study examined the air born uptake of toluene and ethylbenzene by twelve plant species. The examined species were placed in glass chambers with volume of 15.6 L, where toluene or ethylbenzene were injected to generate concentration of 20 ppm (12µmol) inside the chamber.</td>
<td>The toluene removal efficiency was found to average around 77% after 72h of exposure across the twelve-examined species, where the highest toluene removal efficiency of ~85% was found in Sansevieria trifascianata.</td>
<td>All twelve-examined species showed more than 70% toluene and ethylbenzene removal efficiency after 72h of exposure.</td>
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In term of ethylbenzene, the average removal efficiency was found to be ~70% after 72h of exposure between the twelve-examined species. The highest ethylbenzene removal efficiency of ~93% was found in *Chlorophytum comosum*.

| Sriprapat et al. (2013) | The study assesses the potential of *Zamioculcas zamiifolia* to reduce the concentration of benzene, toluene, ethylbenzene and xylene (BTEX) from contaminated indoor air. The plants were exposed during 72h to contaminated air containing one of each of tested compounds in a glass chamber. The concentration of each of the tested contaminants were 20 ppm. During the test the chamber were kept at 32±5°C with 12h natural light-dark cycles. | The study found that *Zamioculcas zamiifolia* plants was effective in decreasing the studied compounds in the contaminated air within 120h. The BTEX removal efficiency of the studied specie was found to be 0.96±0.01 mmol/m² for benzene, 0.93±0.02 mmol/m² for toluene, 0.92±0.02 mmol/m² for ethylbenzene and 0.86±0.07 mmol/m² for xylene during 72h of exposure. The study also reported that 80% benzene, 76% toluene, 75% ethylbenzene, and 73% xylene were removed by stomata, while 20, 23, 25, and 26% of them were removed by non-stomata pathways or cuticles, respectively. | *Zamioculcas zamiifolia* has the potential to reduce the concentration of BTEX from contaminated indoor air. The physicochemical properties of each BTEX may affect its removal. The stromata removal pathways are dominating during BTEX removal. |
Aydogan et al. (2011) | The study evaluated three types of growing media (growstone, expanded clay and activated carbon) and four common interior plants (*Hedera helix* (English ivy), *Chrysanthemum morifolium* (pot mum), *Dieffenbachia compacta* (dump cane) and *Epipremnum aureum* (golden pathos)) for their abilities to remove formaldehyde from air. Formaldehyde uptake of the individual growing media was evaluated under three conditions: dry media, dry media in a pot and wet media in a pot. A clear glass chamber at constant temperature of 21 ± 1°C was used. Artificial lighting was provided during the experiment using a fluorescent bulb in 12h cycles (day/night). A stream of formaldehyde vapours was injected to the chamber resulting initial formaldehyde concentration of ~1.63 ppm (~2000 µg/m³) inside the chamber where the selected growing media and plans were exposed.

|  | The formaldehyde removal efficiency of activated carbon measured after 10h were 97.6%, 94.1%, and 88.9% for dry media, dry media in a pot and wet media in a pot, respectively. The removal efficiency of the other two media were 26.4%, 47.5%, 62.6% (expanded clay) and 17.4%, 39.3%, 62.3% (growstone) for dry media, dry media in a pot and wet media in a pot, respectively. the total reduction of gaseous formaldehyde of the examined plant species achieved by aerial parts (AP), the root zone (RZ), and the entire plant (EP) in a 24h period was as following: for *Hedera Helix* - 81% (AP), 85%(RZ), 88%(EP); for *Chrysanthemum morifolium* - 92% (AP), 88% (RZ), 84% (EP); for *Dieffenbachia compacta* - 92%(AP), 92% (RZ), 96% (EP); and for *Epipremnum aureum* - 95% (AP), 93% (RZ), 94% (EP).

|  | From the three-growing media studied, activated carbon alone showed the highest formaldehyde removal at about 98% for period of 10h. The other two media showed similar formaldehyde removal efficiency of under wet conditions at about ~62%. The four-plant species studied demonstrated similar abilities to remove formaldehyde (around 90%) for 24h period. All four-plant species demonstrated quicker uptake rate of formaldehyde under dark versus light conditions.
| **Duijn et al. (2011)** | The study assessed the effect that plants located in the classroom can have onto the indoor air quality and the people in the room (students and teachers). The study aimed to investigate the effects of plants in the classrooms on the five following categories:  
1) Effect onto the IAQ of the classroom: in term of relative humidity, temperature, CO₂ and formaldehyde concentrations.  
2) Effect on the well-being of the students in the classroom (subjective experience)  
3) Effect on learning performance of the students (objective effects on both creative and standard tasks)  
4) Effect on the work performance, well-being and health of the teachers  
5) Effect on education regarding nature conservation, sustainability and experience of nature | The overall results from the study showed:  
- 10% – 20% CO₂ concentration removal in classrooms with plants in comparison with these without plants  
- The control condition tests of formaldehyde removal rate of *Spathiphyllum* showed:  
  20 mg formaldehyde per hour removal rate for 5000 g leaf mass  
  The formaldehyde removal rate was relatively constant regardless light conditions  
- 7% less health complaints from the students and teachers | Based on the obtained results, the study concluded:  
1. The present of plants in the class room and enough light (> 15 PAR) the study documented  
- 10% -20% reduction of CO₂ concentrations  
- 7% less health complaints from the students and teachers  
- 20% better score in performed creativity tasks and tests  
- The air purifying effect from the plants reduces the “bad odours” to a 0 level within 45 min  
2. The positive effects on air purification from the plants are still present in lower light conditions (< 15 PAR), but in slower rate.  
- 20% better score in performed creativity tasks and tests  
3. No adverse effects on the state of the pupils' health was observed due to presence of the plants |
| **Kim et al. (2010b)** | The study assessed the efficiency of volatile formaldehyde removal of 86 species of plants from five general classes (ferns, woody foliage plants, herbaceous foliage plants, Korean native plants, and herbs). Phytoremediation potential was assessed by exposing the plants to gaseous formaldehyde (2 µL/L) in airtight chambers (1 m³). Among the 86 species tested, nine (Osmunda japonica, Selaginella tamariscina, Davallia mariesii, Polypodium formosanum, Psidium guajava, Lavandula spp., Pteris dispar, Pteris multifida, and Pelargonium spp.) have shown excellent formaldehyde removal characteristics (e.g., 1.87 µg/m³.cm² or greater leaf area over 5h). In contrast, the average formaldehyde removal among all the species tested was only 1.0 µg/m³.cm² leaf area over 5h or 0.20 µg/m³.h.cm². The tested species showed overall good formaldehyde removal characteristics. However, some of the species were more efficient than others, therefore the authors separated them into three general groups based on their formaldehyde removal efficiency: excellent (greater than 1.2 µg/m³ formaldehyde per cm² of leaf area over 5h), intermediate (1.2 or less to 0.6), and poor (less than 0.6). Species classified as excellent are considered viable phytoremediation candidates for homes and offices where volatile formaldehyde is a concern. |
| **Liu et al. (2007)** | The study screened 73 ornamental plant species for their ability to remove volatile organic compounds from air. The experiment was conducted in a Plexiglas chambers under controlled temperature of 25 ± 10°C and relative humidity of 55 ± 15% with 14h light period. The plants were exposed to a benzene atmosphere with concentration of 150 ± 6.7 ppb. From the 73 tested plant species, 23 did not alter the benzene concentration in air, 13 species removed between 0.1 - 9.99% of benzene in contaminated air, 17 species removed 10-20%, and 17 species removed 20-40%. Three species removed 60-80% of benzene in experimental air. 10 of the species with higher benzene removal were From the 73 tested commonly used as ornamental plant species, 10 have been found to be most effective at removing benzene from air. Crassula portulacea (Crassulaceae), Hydrangea macrophylla (Hydrangeaceae), Cymbidium Golden Elf (Orchidaceae), Ficus microcarpa var. fuyuensis |
additionally tested for two more days (8h exposure per day) to quantify their benzene removal capacity. The determined benzene absorption rates normalized for leaf were as following: *Crassula portulacea* (Crassulaceae) - 503.4 µg/m².min, *Hydrangea macrophylla* (Hydrangeaceae) - 203.9 µg/m².min, *Cymbidium Golden Elf* (Orchidaceae) - 185.7 µg/m².min, *Ficus microcarpa var. fuyensis* (Moraceae) - 177.4 µg/m².min, *Dendranthema morifolium* (Asteraceae) - 142.3 µg/m².min, *Citrus medica var. sarcodactylis* (Rutaceae) - 115.8 µg/m².min, *Dieffenbachia amoena cv. Tropic Snow* (Araceae) - 80.0 µg/m².min, *Spathiphyllum Supreme* (Araceae) - 74.2 µg/m².min, *Nephrolepis exaltata cv. Bostoniensis* (Davalliaceae) - 51.0 µg/m².min, and *Dracaena deremensis cv. Variegata* (Dracaenaceae) - 41.0 µg/m².min. *Moraceae*, *Dendranthema morifolium* (Asteraceae), *Citrus medica var. sarcodactylis* (Rutaceae), *Dieffenbachia amoena cv. Tropic Snow* (Araceae), *Spathiphyllum Supreme* (Araceae), *Nephrolepis exaltata cv. Bostoniensis* (Davalliaceae, and *Dracaena deremensis cv. Variegata* (Dracaenaceae) emerged as the species with the greatest capacity to remove benzene from indoor air.


