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The role of plants in improving indoor air quality

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SUMMARY

Many hours of our days are spent at home or in the office. The indoor environment can present conditions that are not favorable to health, with the accumulation of pollutants and allergens, both produced inside and coming from outside. It is commonly believed that houseplants can play an effective role in removing these pollutants. Different species are taken into consideration in relation to the adsorption capacity, the amount and type of pollutants removed. Plants can remove small amounts of pollutants per hour and per unit of surface area, but when compared to the volume of a room, the result is not very significant. In reality, it seems that the best solution lies in the use of tools aimed at air purification and that plants have a greater importance in creating a pleasant environment and can have positive effects especially from a psychological point of view.

KEYWORDS: Indoor Pollution, Plants, Allergy, Environmental Monitoring

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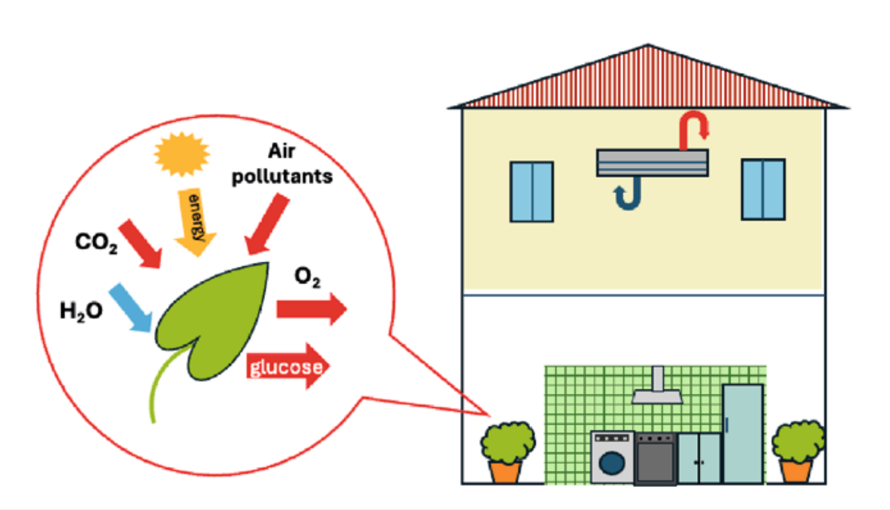

COVER FIGURE. Plants as sources of oxygen and accumulators of pollutants.

INTRODUCTION

The home environment, and in general closed places where one spends a lot of time (school, office, etc.) may suggest the idea of safe places, where one can find shelter from the weather, for example. However, these can be unhealthy, depending on the degree of air exchange, the surface of the windows, the air conditions outside and the activities carried out inside. The sources of pollutants may in fact be external or even internal, determined by the activities of the occupants (such as cleaning the house and cooking food), and by the treatments of the furnishings to the construction materials of the buildings themselves (Cover figure).

Indoor air pollution is, therefore, a growing public health concern, as we spend most of our time indoors [1] and indoor pollutants can have adverse health effects, contributing to respiratory problems, allergies and other diseases.

Prolonged exposure to indoor pollutants can cause a wide range of health problems, including respiratory irritation, allergies, cardiovascular disorders and even neurotoxic effects [2]. Recent studies have shown that indoor pollution can aggravate pre-existing conditions such as asthma and chronic obstructive pulmonary disease (COPD).

Introducing plants in these environment could have positive effects in term of improving health of inhabitants, varying air conditions (humidity) and removal of pollutants [3].

In this paper we want to summarize the state of art about the role of indoor plants.

MATERIALS AND METHODS

Indoor air pollution: sources and effects

Indoor air pollution originates from a variety of sources. The most common indoor pollutants are volatile organic compounds (VOCs), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), and molds.

The main sources of these pollutants are building materials, cleaning products, and internal combustion together with outdoor air pollutants.

Particles of biological origin, such as pollen and spores, must also be added to these substances.

The main sources and the most important effects on human health of these substances can be summarised as follows:

1. VOCs: these are emitted by paints, cleaning products, furniture and other synthetic materials. VOCs, such as formaldehyde, benzene and toluene, can cause eye irritation, headaches and respiratory problems if inhaled in high concentrations;
2. particulate matter: fine and coarse dust produced by indoor combustion (cooking, smoking) or outdoor combustion (traffic, industry, heating) and allergens, such as pollen, biological fragments of animal origin and mold spores, can cause respiratory problems, especially in people with asthma or other pre-existing conditions;
3. carbon dioxide (CO_2): high CO_2 levels in poorly ventilated environments can cause headaches, dizziness and cognitive problems;
4. biological contaminates: mold, bacteria and viruses thrive in damp environments, contributing to allergic reactions and respiratory infections.

These pollutants can have immediate and long-term effects on human health, particularly in indoor spaces with poor ventilation. For this reason, reducing their presence is crucial to maintaining a healthy environment [4].

Today, an increased attention to the choice of materials and design of indoor spaces, with the presence of live plants, use of pastel colors, plenty of light, large windows, both for workspaces (direct relationship better environmental quality of the workplace-better worker performance) and for home spaces, and an increased awareness of environmental issues have focused attention on possible indoor pollutants.

The possibility of reducing indoor pollutants passes through strategies, largely determined by the type of pollutant present or expected.

In general, the most effective strategies to reduce indoor pollution are based on:

- adequate ventilation, preferably with controlled mechanical ventilation (CMV) systems;
- the use of air purifiers with HEPA filters;
- the reduction of indoor sources of pollution with, for example, the use of low VOC-emitting paints and environmentally friendly cleaning products;
- air quality monitoring to identify and reduce pollutant concentrations.

Indoor plants and indoor pollution

A common, and rather well-established, belief is that there are plants that can absorb pollutants.

A classic and common example is *Tillandsia usneoides* (L.) L. or old man's beard, a Bromeliads, often sold as a smoke-eating plant. This epiphyte appears to have a high capacity to absorb radon [5]. The nomenclature of the different species mentioned has been verified and updated according to the IPNI [6].

On the other hand, bibliographic researches on search engines show a progressive and consistent number of scientific publications on this subject [7-11]. Most of the works present laboratory experiments with different species and for certain pollutants. Analyzing the list of species considered, it emerges that C3 (see below) plants are most commonly used.

Similarly, many articles describe the improvement of individual well-being determined by the presence of plants that make the environment in which one lives more comfortable, even from a perceptual point of view [12,13].

These considerations gave rise to the idea of writing this contribution to take stock of current knowledge and the actual efficacy of certain plants commonly indicated as capable of removing airborne substances.

How plants work

Plants are autotrophic organisms, i.e., they can produce chemical energy from solar radiation through a complex process found in certain groups of bacteria, algae and higher plants. Much of life on Earth as we know it today depends on the products of photosynthetic reactions that fix CO_2 into organic compounds. In many cases, this process releases molecular oxygen as 'waste'. The evolution of photosynthesis was the cause of the transformation of the earth's primordial atmosphere from a reducing to an oxidizing environment. Thanks to this ability, they are able to produce glucose from water and carbon dioxide:

$6\,CO_2 + 6\,H_2O$----> light ----> $C_6H_{12}O_6 + 6\,O_2$

This simply stated reaction is quite complex and is called photosynthesis.
The intuition and discovery of this process can be attributed to Van Helmont, a Belgian scientist in 17th-century.
Photosynthetic organisms convert about 110-115 gigatons of carbon per year into biomass, extracting CO_2 which is converted into organic matter and then removed from the atmosphere [14].
Photosynthesis takes place on the thylakoids of chloroplasts, organelles exclusive to autotrophic organisms. Thanks to the presence of pigments within them, chlorophylls are capable of absorbing well-defined wavelengths. The pigments absorb on blue-violet and red-orange wavelengths.
The green wavelengths are reflected, giving the leaves their color. It is surely one of the wonders of nature that out of the entire frequency range of energy from the sun, only a small band, the visible, is used for this process.
The absorbed energy is used to break down the water molecules absorbed by the roots, releasing oxygen into the atmosphere.
The energy produced is used during the Calvin cycle to assemble CO_2 molecules into sugar molecules. This construction takes place in the stroma; the matrix presents in the chloroplasts in which the thylakoids are immersed. Driving the cycle is the presence of the world's most widespread protein, ribulose-1,5-bisphosphate carboxylase/oxygenase or Rubisco. Its role is crucial for the construction of sugar molecules.
In the mitochondria, cellular respiration takes place, resulting in the release of carbon dioxide. However, the balance between absorbed and emitted gas is favorable. Gas exchange takes place through the opening and closing of the stomata, openings delimited by two cells called guard cells, which are present in large numbers on leaves. Through these openings the exchange of oxygen, carbon dioxide, water vapor and of course whatever is present in the atmosphere takes place.
It must be said that plants do not all carry out photosynthesis in the same way: there are C3 plants, C4 plants and those called CAM (Crassulacean Acid Metabolism, plants from very hot, water-poor extreme environments), depending on their metabolism.
It is the result of a long evolution linked to the variation in the average temperature of the atmosphere and consequently the concentration of CO_2 in the atmosphere.
In C3 plants, CO_2 enters the stomata and is directly utilized in the Calvin cycle, while in C4 plants CO_2 enters at night and is utilized in the Calvin cycle during the day. In CAM plants, it is absorbed and stored at night and then utilized during the day, without opening the stomata, which saves water.
In relation to these adaptations, for example, the opening time of the stomata for gas exchange varies. The introduction of plants can determine small variations in temperature and especially humidity during the year; furthermore, we must consider the role of air conditioning in winter and summer, which can transform domestic air [3,11].
It is also known that tree plants can be used in the urban environment for various purposes, including being resistant to pollution.
This action can be passive; dust is deposited on the leaves and gaseous substances can be absorbed through stomata and either be accumulated or metabolized.

Phytoremediation

The use of plants for remediation or reclamation of an area due to their ability to absorb particularly polluting substances is called phytoremediation [15].
Atmospheric phytoremediation refers to the use of plants to remove pollutants in the air. It is specific to each plant species, being a function of various genetic, physiological, anatomical and morphological parameters and microbe-plant interactions. It is carried out by plants through stomata, leaf surfaces, soil and microbes [16-18].
This capacity or potential of plants can be extended to water or air.
Furthermore, the simultaneous use of different species can, by simulating species diversity as occurs in nature, optimize the capacity of the system [19].
In terms of how pollutants are removed, according to the literature[16] we have:

- non-stomatal adsorption: accumulation of air pollutants both on the surface layers of the leaves (e.g. wax deposition) and on the soil surrounding the plants, following degradation by the microbial communities inhabiting the phyllosphere and rhizosphere;
- stomatal uptake: a pathway for the absorption of air pollutants through a leaf, followed by active processes of biochemical degradation, detoxification by enzymes and possible conversion into various bioproducts within the plant or in the rhizosphere;
- plant microbiome: originally defined as the set of genomes belonging to the entire plant-associated microbiota (including microorganisms present in the rhizosphere, phyllosphere or within endophytic compartments). This term is now often used to refer to the microbial community itself (such as bacteria, fungi and viruses).

Most of the studies consulted refer to two main strategies: the use of indoor pot plants and the adoption of outdoor plant barriers, which

we might summarily call green walls or vertical greenery. This second type is to be imagined mainly in new buildings, combined with strategies to control the temperature inside the home.
The trace components of indoor air are mainly: carbon monoxide and dioxide (CO and CO_2), nitrogen oxides (NO and NO_2), ozone (O_3), VOCs (e.g. formaldehyde, acetaldehyde, benzene, toluene, xylene, acrolein and styrene), polycyclic aromatic hydrocarbons (PAHs), secondary organic aerosols (SOAs) and atmospheric oxidants (O_3, OH and NO_3 radicals).

Some numbers

Every day we breathe in an average of 14,400 liters of air, which is composed of approximately 78% nitrogen, 20.9% oxygen, 0.04% carbon dioxide and a number of other gases (noble gases).
Inhaled air contains just 21% oxygen. That exhaled is only 17%. Carbon dioxide increases from 0.04% to 4%. So, on average, a man inhales 2,600 liters of O_2 and 5.76 of CO_2 in 24 hours. On exhaling, CO_2 increases to 4%, releasing 576 liters. We can say that we also contribute to indoor pollution.
An 80 square meter flat with a ceiling height of 2.8 m has a volume of air of roughly 224 cubic meters in which our objects are located and in which we move around breathing in the gaseous mixture to which we add all the pollutants that may come from outside or inside.
The idea of using plants to purify the air in indoor spaces is rather dated.
In a NASA study dating to 1989 [20] when the final report was published on the studies, it started a good 16 years earlier, conducted to evaluate the use and best species to reduce indoor pollution, it was already referred to as Sick building syndrome.
Similar studies had also been initiated in the USSR, in the Siberian Grasnoyarak laboratories by Prof Gitelson's team [21].

Which plant to use?

A few species were chosen, which are also quite common in our homes:
Chamaedorea seifrizii Burret, *Ficus benjamina* L., *Hedera helix* L., *Gerbera jamesonii* Bolus ex Hook.f., *Dracaena fragrans* (L.) Ker Gawl., *Dracaena reflexa* var. angustifolia Baker, *Dracaena deremensis* Engl, *Sansevieria laurentii* De Wild., *Spathiphyllum wallisii* Regel, *Spatiphyllum x* Mauna Loa, *Chrysanthemum morifolium* (Ramat.) Hemsl.
These, as well as others that will be mentioned later, are mainly plants that we can observe in the tropical greenhouses of botanical gardens, thus always green with expanded leaf, adapted to low light conditions, demanding moisture and less special care: ideal for busy flat dwellers. Periodical simply dusting the leaves shows how much dust is deposited on them and how little they contribute to absorption due to reduced stomatal opening and closing activity.
Plants capable of removing VOCs and other pollutants (modified from literature [18]) are reported in Table I.
It should be noted that the quantities removed are in the order of micrograms per hour and that the measurements refer to 'controlled room' experiments. Furthermore, when we talk about the capacity of a species to remove a certain substance, the value is expressed in mg per square meter of leaf. A quick mental calculation allows us to understand what the surface area in square meters of a *Ficus benjamina* plant could be: approximately 9-10 cm^2 per leaf, if our *Ficus* has 1000 leaves it can perhaps reach a total leaf surface area of approximately 1 m^2.
According to literature it is possible to describe different way phytoextraction, phytodegradation, and phytovolatilization, phytostabilization, rhizodegradation, and rhizofiltration. Plants acts as hyperaccumulators, absorb pollutants from the growing medium (rhizosphere) and transport them to the leaves and other aerial parts of the plant (phyllosphere); this phytoremediation strategy is known as "phytoextraction" [18,22].
Curtis Gubb [23] suggested that potted plants such as *Spathiphyllum wallisii 'Verdi', Dracaena fragrans* 'Golden Coast' and *Zamioculcas zamiifolia* (G. Lodd.) Engl. can remove NO_X from indoor, but the removed quantity can influenced with variation of concentration due to opening of windows, while VOC concentration indoors does not seem to have the same positive role [24].

Houseplants and allergies

Some houseplants can cause allergic reactions that mostly affect the respiratory system (rhino conjunctivitis, bronchial asthma) or the skin (contact dermatitis). Among the many species of houseplants that most frequently cause allergic reactions are widespread domestic plants such as *Euphorbia pulcherrima* Willd. ex Klotzsch (poinsettia)[25], which mainly causes contact dermatitis; the yucca cactus, dieffenbachia, in whose tissues there are cells, very rich in calcium oxalate, which crystallized in the form of very thin needles called raphides.
Slave traders used it both to punish them and to prevent them from screaming during the crossings from Africa to the Americas. Chewing causes violent inflammation of the mucous membranes of the mouth and tongue, with burning, swelling and copious salivation.
Sometimes the swelling also affects the epiglottis and the surrounding area, resulting in death by asphyxia. *Hoya carnosa* (L. f.) R.Br. (wax flower), on the other hand, gives rise to symptoms mainly affecting the respiratory system, while the spateflower (*Spathiphyllum wallisii*) may be responsible for symptomatic manifestations involving both districts [26].
Other plant specimens more frequently implicated in the onset of allergic manifestations are the philodendron (*Philodendron bipennifolium* Schott and *Philodendron scandens* K. Koch & Sello) responsible for both clinical pictures, respiratory and dermatological [27] as well as the *Schefflera actinophylla/arboricola* (*Heptapleurum actinophyllum*) (Endl.) Lowry & G.M. Plunkett [28,29] and the *Dracaena* sp. [30], while both *Primula obconica* Hance and the orchidaceae generally only cause cutaneous contact reactions. *Ficus benjamina* [31,32] a green plant of tropical origin that belongs to

TABLE I. List of some plants by their scientific name, common name, family in alphabetical order by family and type of pollutants each species can remove.

Species name	Common name	Family	Pollutants
Aloe vera (L.) Burm.f.	True aloe	Asphodelaceae	Formaldehyde, benzene
Chlorophytum comosum (Thunb.) Jacques	Phalanx or spider plant	Asparagaceae	Xylene, toluene, formaldehyde, CO, benzene
Chrysanthemum morifolium (Ramat.) Hemsl.	Garden mum or Florist's chryanthemum	Asteraceae	Xylene, toluene, formaldehyde, benzene, trichloroethylene
Dracaena trifasciata (Prain) Mabb.	Snake-plant	Asparagaceae	Xylene, toluene, formaldehyde, benzene, trichloroethylene, ammonia and CO
Dypsis lutescens (H.Wendl.) Beentje & J. Dransf.	Golden cane palm	Arecaceae	Xylene, CO, formaldehyde, trichloroethylene, toluene
Epipremnum aureum (Linden & André) G.S.Bunting	Golden pothos	Araceae	Xylene, trichloroethylene, toluene, formaldehyde, benzene
Ficus elastica Roxb. ex Hornem.	Rubber fig	Moraceae	Formaldehyde
Ficus benjamina L.	Weeping fig	Moraceae	Xylene, toluene, formaldehyde
Gerbera jamesonii Bolus ex Hook.f.	Gerbera daisy	Asteraceae	Formaldehyde, benzene, trichloroethylene
Nephrolepis exaltata (L.) Schott	Boston fern	Nephrolepidaceae	Xylene, toluene, formaldehyde
Spathiphyllum wallisii Regel	Spateflower or peacelily	Araceae	Xylene, trichloroethylene, ammonia, formaldehyde, benzene

the Moraceae family and is often used in domestic environments for ornamental purposes, deserves a separate discussion. From an allergological point of view, Ficus can cause allergic reactions, especially in professional growers. In certain regions, especially in Northern Europe, a significant prevalence of allergic sensitization can be observed among these workers[33].

In certain regions, especially in Northern Europe, a significant prevalence of allergic sensitization can be seen among these workers. This is the case, for example, in Sweden, where sensitization to *Ficus* reaches numerically the same magnitude as sensitization to the most common mold, *Cladosporium*; this sensitization leads to a risk of allergic disease in about half of the sensitized subjects and sometimes also occurs in atopic subjects, but not occupationally exposed.

The main allergen of *Ficus benjamina* is generally found in the sap of the plant, the so-called latex, although it is sometimes quite frequently found both in the dust collected from the leaves of the plant and in the dust on the floors of the rooms where the plant is planted. It is interesting (and has been known for some time) that there is a cross-reactivity between the latex produced by *Ficus benjamina* and the even better-known latex produced by *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg., gum tree, a plant belonging to the Euphorbiaceae family, plants that produce a sap that can sometimes cause allergic manifestations. This family has more than 2,000 species, including cacti and other succulent garden plants; the sap produced by these plants, which resembles white latex, can indeed cause urticarial manifestations, eyelid edema, allergic rhino conjunctivitis and bronchial asthma. The Cover figure shows the role of plants and possible sources of indoor pollution.

RESULTS AND DISCUSSION

How to effectively reduce indoor pollution

According to [34,20] it was recommended to use two plants in each room of 9.3 m^2, but we think that for indoor pollutants it is essential to implement a series of interventions and prevention measures based on individual behavior and technical aspects that can reduce the formation and accumulation of chemicals as much as possible.

Good individual habits include to effectively reduce indoor pollution include:

- constantly airing the rooms by favoring the entry of so-called primary air so as to allow the dilution of indoor pollutants either by acting directly on the windows, or by installing 'controlled mechanical ventilation' systems that expel exhausted indoor air to introduce outside air, after heating or cooling, depending on the season. It should be emphasized that window openings

should be made at times when outdoor pollutants are least produced;
- always maintain a relative humidity level between 44% and 55% and a temperature between 18° and 22° to minimize the formation of mold and bacteria that can lead to allergies and respiratory problems. Proper ventilation of rooms will reduce the presence of dust and microorganisms;
- reduce exposure to second-hand smoke: smoking should be avoided altogether in domestic indoor environments;
- when cooking food (extractor hoods) keep windows open whenever possible;
- use cleaning and maintenance products (paints, varnishes, solvents, etc.) only as long as strictly necessary, in the smallest possible quantities, and ventilate the rooms constantly;
- maintain sufficient cleanliness of the rooms so as to reduce the presence of mold and household allergens (dust mites and pet epithelial derivatives) as much as possible.

There are also preventive actions based on the use of products with low pollutant emissions, such as VOCs, for normal painting or varnishing of rooms or special building materials capable of absorbing pollutants such as:
- sheep's wool, an eco-friendly insulation material, that simultaneously provides the environment with a constant climate in summer and winter, and a better quality of life as it significantly reduces draughts, mold and moisture;
- biobricks made of lime and hemp, which is also able to absorb moisture without retaining it thanks to its many air-filled micropores;
- interior finishes based on clay, milk or egg yolk that can absorb VOCs, dust and neutralize odors;
- mineral paints capable of capturing and transforming formaldehyde present in rooms.

Possible technical interventions capable of acting on indoor microclimate conditions are:
- the installation of door and window insulation systems to reduce the direct entry of polluted outside air, while taking care to maintain an appropriate air exchange;
- the use of air-conditioning systems equipped with HEPA (High Efficiency Particulate Air Filter) filters for suspended particles down to 0.1 microns, active carbon filters, ionizing filters that attract dust, and 'UVGI' filters that exploit ultraviolet light and are able to destroy bacteria and pathogens;
- use electronic systems capable of 'purifying' the air such as:
  - ozonators which, without any filter, exploit ozone's ability to eliminate pollutants. In this case, however, care must be taken with the operation of the device, as an excessive amount of ozone can in turn be harmful to people;
  - cold plasma' systems, which, by ionizing the air, are able to eliminate pollutants without emitting any substance into the environment;
  - photocatalysis systems, which thanks to a natural photochemical reaction are able to eliminate both VOCs and bacteria.

Of course, it is necessary to ensure periodic cleaning and maintenance of the filtration systems as per the air conditioning equipment user manual in order to prevent the spread of pathogens that could settle on interior surfaces.

CONCLUSIONS

Indoor plants are often considered a natural solution for improving air quality [35]. Pioneering studies such as the aforementioned NASA work have shown that some plants can absorb VOCs such as benzene, formaldehyde and xylene. However, more recent research has raised doubts about the effectiveness of plants in real environments.

According to an analysis published in Nature Sustainability [24] the effectiveness of plants in reducing indoor pollutants is limited compared to mechanical ventilation systems and HEPA filters. The study found that hundreds of plants per square meter would be required to achieve a significant impact.

Although indoor plants have an undoubted beneficial, aesthetic and psychological effect, their contribution to reducing indoor pollution is limited [36]. We must also remember that it is important to periodically remove dust from the surfaces of the leaves, as we do with our furniture, both to maintain their bright green and to not reduce the efficiency of photosynthesis.

Technological approaches, such as mechanical ventilation and air purifiers, remain the most effective solutions to ensure a healthier indoor environment.

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Conflicts of interest statement

The authors declare no conflict of interest.

Authors' contributions

AT, ADG and ADMDB drafted and revised the manuscript for important intellectual content; all co-authors actively participated in the discussion and critical revision of the manuscript. All authors contributed to the drafting of the article and approved the submitted version.

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