

## Review

# Benefits of Using Plants in Indoor Environments: Exploring Common Research Gaps

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**Abstract:** The introduction of green plants in indoor spaces has raised a great amount of interest motivated by plants' supposed capacity to improve the quality of indoor built environments. Subsequent studies have covered a broad range of topics, testing plants in indoor environments for their climate-mitigating effects, acoustic benefits, potential energy savings and the enhancement of the indoor microbial communities. Despite the diversity of focus in these studies, no major breakthroughs have been made involving the use of plants in indoor environments after nearly thirty years of research. To identify major inconsistencies and gaps in the research, this review, of an explorative nature, presents an analysis of plant-related parameters reported in 31 cases of experimental research involving the use of plants in indoor environments. The papers were identified by searching the online databases Google Scholar, ResearchGate, Scopus and MDPI and were selected based on their relevance to the topic and diversity of focus. Two classifications in table form provide an overview of the 38 plant-related parameters used in the reviewed research. The conclusions drawn from the analysis of the tables highlight a strongly anthropocentric frame of reference across the majority of the studies, which prioritize human and experimental convenience above plant physiology, and display an overall scarcity and inconsistency in the plant-related parameters reported.



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**Keywords:** indoor environment; plants; greenery; parameters; benefits

## 1. Introduction

The introduction of green plants in indoor spaces has raised a great amount of interest motivated by the positive physiological and psychological benefits for humans [1]. The psychological and physiological benefits of human–nature contact include a great number of therapeutic and restorative effects [2] ranging from stress reduction to the development of cognitive and social skills [3]. Studies on biophilic workspaces have shown to positively affect occupants' attitudes and behaviors and improve their overall wellbeing, satisfaction and happiness [1] with rebound effects on performance and productivity [4]. Subsequently, living greenery has become a matter of interest for its effects on the physical quality of the built environment itself beyond its aesthetic appeal [5].

A large majority of previous work has focused on plants' supposed capacity to improve indoor air quality (IAQ)—whether through the removal of indoor air pollutants [1,6–11], CO<sub>2</sub> adsorption [12] or ion regulation [13]—reaching no scientific consensus, although many studies claim to have found positive correlations. Some studies have been very critical, pointing out both low removal rates [14] and methodological inconsistencies [8,14] in large part due to important environmental differences in conditions between real indoor environments and the experimental chambers where tests have been conducted.

All other effects of living plants on the indoor environment have received, in comparison, much less attention.

Plants have been found to have climate-mitigating effects such as thermal [15] and humidity control [1,15,16]—as a direct consequence of the evaporative cooling, differential shade cooling and solar gain heating of the foliage canopies [16]—and also contribute to potential energy savings [17].

Plants have been suggested as effective passive acoustic insulators, reducing sound levels through the reflection, dispersal, absorption or interference of sound waves by vegetation and growth media [1,18,19].

Finally, plants have also been suggested to be important but underutilized sources for the enrichment of indoor microbial communities. As microbial diversity is thought to be a key aspect for plants as well as for human health, the application of soil microbes to increase the metabolism of indoor plants is suggested as a way to positively alter the quality and the quantity of the microbial community within the built environment [20].

Despite this diversity of focus in studies on the benefits of plants to human health and indoor environmental quality, no major breakthroughs have been made involving the use of plants in indoor environments after nearly thirty years of research. With this in mind, the author decided to conduct a brief analysis of the plant-related parameters reported in 31 cases of experimental research focusing on different consequences of introducing plants in indoor environments. The aim is to identify major inconsistencies and gaps in the research involving plants in the built environment.

## 2. Materials and Methods

This work is of an exploratory nature. It aims to highlight existing incongruences and gaps and to present researchers in the field with new and maybe different criteria of research, opening up new perspectives. Therefore, rather than presenting a complete review of the last thirty years of experiments on the effects of plants in indoor environments, the author focused on fewer case studies, highlighting established research methods.

### 2.1. Selection of Studies Reviewed

In a first approach to the topic, the online databases Google Scholar, ResearchGate, Scopus and MDPI were screened for studies involving the use of plants in indoor experimental research settings using different combinations of the keywords “greenery/plant/living wall/vertical garden/indoor/environment/spaces/lab/experiment/benefits/health/climate/temperature/heat/humidity/acoustic/psychological/mental/health/stress”.

In the second phase, studies of major interest were selected out of the larger pool of studies found. The criteria that needed to be fulfilled to pass the second phase of selection were the following:

- Studies should focus on indoor environments.
- Studies should report on the experimental research setting (lab or real conditions). Review articles and most books were therefore excluded.
- Studies should use live plants that are able to interact with the study environment. Research using different kinds of simulated or displayed greenery (VR, pictures, window views, etc.) as well as studies using cut flowers were therefore excluded from the selection.

In the third phase of selection, studies were classified based on their focus (air quality, climate, acoustics, mental health) and the experimental conditions (lab or real environment). The aim was to preserve the diversity of the effects of plants studied within the review and therefore also the variety of the methods adopted, rather than representing the focus of the studies in a proportional way. As a consequence, the overwhelming quantity of studies available on plants' capacity to purify air, or on the psychological benefits of proximity to greenery, are only partially (and not proportionally) reflected in the analysis.

In the fourth phase, the selection was further narrowed down within each category, according to the credibility of the source (peer review, journal articles preferred over conference articles, number of citations). Additionally, in articles presenting comparable experimental settings, the more recent articles were preferred. No other temporal limit was set within the selection, with the assumption that interesting testing conditions might be found regardless of the year of publication.

Finally, the remaining selection was scanned for the articles that seemed to cover the largest diversity of testing conditions.

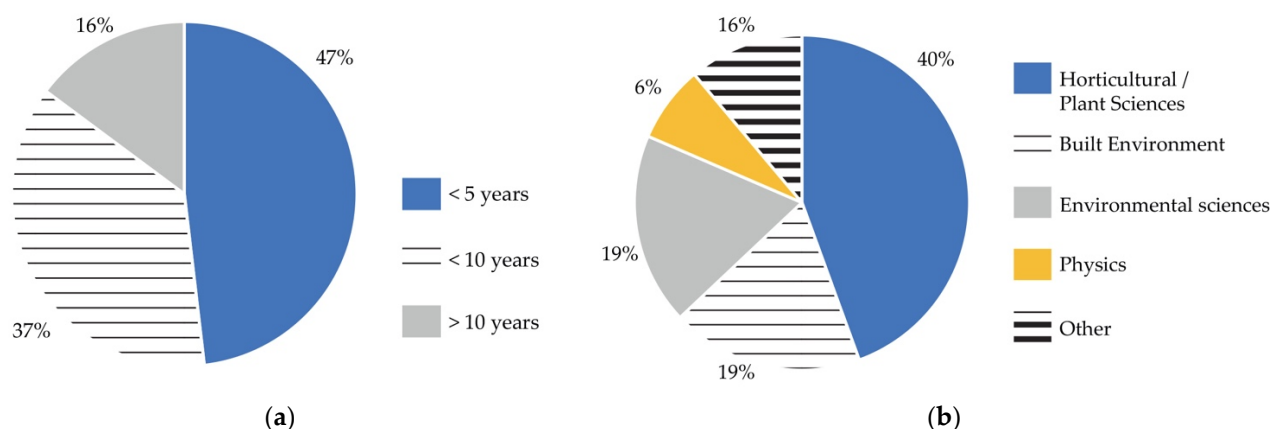
As a result, 31 sources were identified (Table 1).

**Table 1.** Studies reviewed, organized according to focus and experimental conditions.

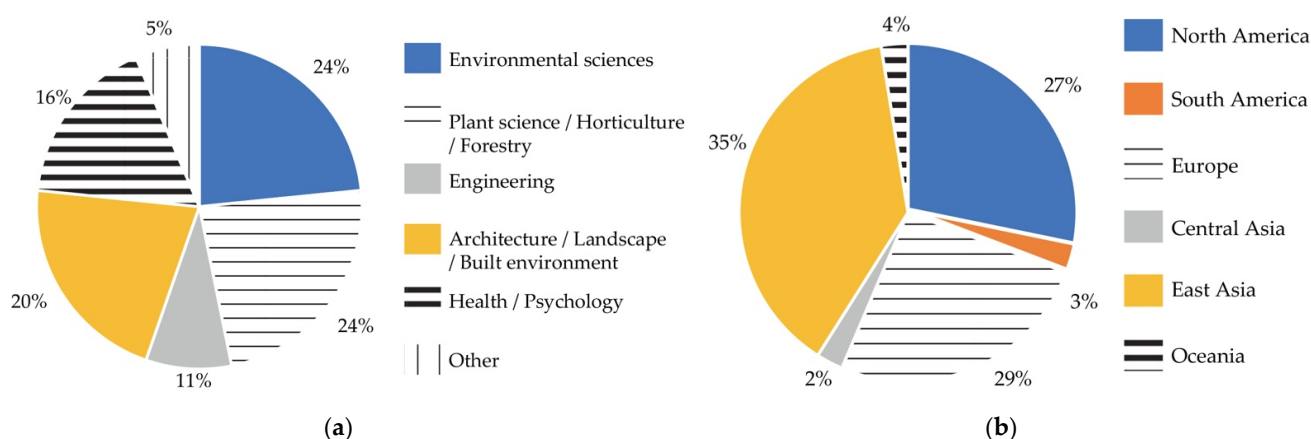
| Focus         | Experimental Conditions | Sources (Alphabetically)       |
|---------------|-------------------------|--------------------------------|
| Air quality   | Lab environment         | Abbass et al. [21]             |
|               |                         | Burchett [22]                  |
|               |                         | * Han [23]                     |
|               |                         | Irga et al. [24]               |
|               |                         | Kim et al. [25]                |
|               |                         | * Salamone et al. [26]         |
|               |                         | Schmitz et al. [27]            |
|               |                         | Sevik et al. [28]              |
|               |                         | Wolverton et al. [9]           |
|               |                         | Yang et al. [29]               |
|               |                         | Yang et al. [10]               |
|               |                         | Yoon et al. [11]               |
|               | Real environment        | Pamonpol et al. [17]           |
|               |                         | Roi-Et and Chaikasem [30]      |
|               |                         | * Schempp et al. [31]          |
|               |                         | Sinicina et al. [13]           |
|               |                         | * Smith and Pitt [32]          |
| Climate       | Lab environment         | De Lucia et al. [33]           |
|               |                         | * Han [23]                     |
|               |                         | * Salamone et al. [26]         |
|               | Real environment        | Gunawardena and Steemers [16]  |
|               |                         | * Fernández-Bregón et al. [34] |
|               |                         | Ren and Tang [35]              |
|               |                         | * Schempp et al. [31]          |
|               |                         | * Smith and Pitt [32]          |
| Acoustics     | Lab environment         | Son et al. [36]                |
|               |                         | Asdrubali et al. [18]          |
|               | Real environment        | * Salamone et al. [26]         |
| Mental health | Lab environment         | * Fernández-Bregón et al. [34] |
|               |                         | Choi et al. [37]               |
|               |                         | * Han [23]                     |
|               |                         | Hassan et al. [38]             |
|               |                         | Park et al. [39]               |
|               | Real environment        | * Yin et al. [3]               |
|               |                         | Bringslimark et al. [40]       |
|               |                         | Korpela et al. [41]            |
|               |                         | Lee et al. [42]                |
|               |                         | * Schempp et al. [31]          |
|               |                         | Schoemaker et al. [43]         |
|               |                         | Toyoda et al. [44]             |
|               |                         | * Yin et al. [3]               |

\* study reporting on more than one aspect/type of environment.

A brief analysis of the papers selected was performed in order to provide a context for the research described in them. Figure 1 shows relevant information concerning the publication in terms of year and field of research. Figure 2 focuses on information on the authors themselves (their affiliation) such as their field of study and nationality.



**Figure 1.** Information pertaining to the publication of the studies reviewed: (a) year of publication; (b) field of publication, intended as the field(s) of research that the platforms of publication refer to.



**Figure 2.** Information pertaining to the authors of the studies reviewed and to their affiliation: (a) authors' field(s) of expertise, intended as the name of the department or school mentioned in the affiliation; (b) geographical area that the academics belong to, intended as the geographical area of the universities listed in the affiliations and not as the authors' countries of origin.

## 2.2. Parameter Selection and Description

In the first phase, all parameters that were considered relevant to the plants used in the reviewed experiments (referring to the nature, state and conditions of the plants) were noted, with reference to the specific source, and successively reorganized and combined with the aim to display the sensibility of the authors to specific types of information rather than listing all specific parameters used. For this reason, many parameters that share similarities and purpose (in the specific studies) are classified together, although they are potentially very different and hence not directly comparable. This is the case of the number of plants/number of pots; of plant weight; of leaf area and plant density; and of the concepts under “metabolic capacity”.

To improve the readability of the analytic tables (Table 2 and Table S1), some parameters initially taken into consideration were, in the second phase of analysis, omitted.

**Table 2.** Plant-related parameters identified, classification and definitions.

| Classification/Parameter   | Definition/Notes                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Type of greenery           | Identifies the typology of growing conditions of the plant. This aspect in the classification helps to indicate not only the type of plant, but also the size of the growing medium as well as the maintenance effort.                                                                                                                                                                                             |
| Potted                     | Plants (mostly single plants) growing in pots made out of different materials, from clay to plastic.                                                                                                                                                                                                                                                                                                               |
| Vertical greening          | The papers reviewed refer mostly to “green facades” (vegetation growing against vertical surface) and “living walls” [5,26,33]—or “green wall” [34]—where the plants root in a structural support anchored to the host building.                                                                                                                                                                                   |
| Growth without soil        | The papers reviewed refer mostly to “hydroculture” and “hydroponics”, which are both systems growing plants in nutrient-enriched water solutions. Aeroponic growing techniques were not mentioned in the studies reviewed.                                                                                                                                                                                         |
| Growth on ground           | Indoor environments rarely allow plants to grow directly on the ground. In this case, the repurposing of a greenhouse as an office and living space constitutes an interesting exception [31].                                                                                                                                                                                                                     |
| Epiphytes                  | Plants that naturally grow aboveground, supported non-parasitically by other plants or objects, and absorb water and nutrients from the atmosphere.                                                                                                                                                                                                                                                                |
| Quantity of greenery       | Identifies the measures used to quantify and compare different types of greenery.                                                                                                                                                                                                                                                                                                                                  |
| m <sup>2</sup> (of plants) | The unit of measure, typically used to describe living walls, refers to the size of a (vertical) surface covered with an unspecified number of plants.                                                                                                                                                                                                                                                             |
| Plants/m <sup>2</sup>      | The unit of measure reports the number of plants present within a set area. It is used to describe living walls [13,16,26,34] as well as the plants present within an architectural space [36].                                                                                                                                                                                                                    |
| Index of greenery          | Different measures of the human perception of greenery within a scene. The index of greenness (in %) is calculated on a flat surface (a photo), taking into account the angle of vision of a person [37]. The Green View Factor (GVF) is calculated as a fraction (dimensionless between 0 and 1) of a hemispheric surface being the fisheye caption of the indoor space [26].                                     |
| Number of plants/pots      | The unit of measure refers to the number of plant individuals, regardless of species or size. In the reviewed works, some authors tend to report the number of pots [40,43], with the assumption that each pot contains one individual plant. In Irga et al. [24] each pot is planted with two plants to compensate for eventual losses, which are not further specified.                                          |
| Height of plants           | Length (cm) of a plant, measured from the ground surface.                                                                                                                                                                                                                                                                                                                                                          |
| Size of pot                | The unit of measurement refers to the volume enclosed within the pot in cm <sup>3</sup> [29], although most authors report only the diameter of the pot [10,11,21,23–25,30]. This is used to give an indication of the size of the plant [10,39] and (supposedly) of its root system.                                                                                                                              |
| Weight                     | The category includes different attempts of quantifying greenery on a mass basis. Fresh weight is the gross weight of the plant (often leaves and shoots), including the water content [22,24,27]. Dry weight is the gross weight of the plant (often leaves) after all its water content has been removed by drying [10,22,24].                                                                                   |
| Leaf area/density          | The category includes different attempts of quantifying greenery based on the leaf coverage of a plant. Aspects taken into consideration include (i) leaf “size” in terms of area or surface [11,13,18,21,22,24,25,27–30,37], leaf length [33], and leaf volume [28]; (ii) leaf “quantity” in terms of mass [27] and volume occupied [36] (supposedly, by the leaf canopy including the air space between leaves). |
| Quality of greenery        | Identifies the measures used to describe and qualify the plants used.                                                                                                                                                                                                                                                                                                                                              |
| Species                    | The binomial name identifying the specific group that the plant individual belongs to within the taxonomic classification.                                                                                                                                                                                                                                                                                         |
| Plant combinations         | Juxtaposition of two or more plant individuals with the purpose of obtaining a combined effect from the plants. These can be of the same [13,18] or of different species [31,33], and can grow in the same [13,18,31] or in separated mediums [33].                                                                                                                                                                |
| Plant maturity             | For the purpose of this classification, all definitions of plant maturity were included: (i) life stage (seed, germination, growth, flower, fruit, etc.) [9,10,22,30,31]; (ii) age (days, weeks, years from being sown/to maturity) [25,30,36]. This parameter, wherever included, can give important information as to the plant’s capacity to develop, as well as to its interaction with the environment.       |

Table 2. Cont.

| Classification/Parameter | Definition/Notes                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| General plant health     | Absence of any apparent disease, harmful pathogens and parasites or ill-growth during the experiment.                                                                                                                                                                                                                                                                                                                                                |
| Growing medium           | Composition of the growing medium as well as any nutrients added to the solution.                                                                                                                                                                                                                                                                                                                                                                    |
| Metabolic capacity       | Processes indicative of the plant's capacity of maintaining life. The most referred-to process in the reviewed research was the "photosynthetic rate" [11,22,36], followed by the "chlorophyll concentration" [33] and the "respiration rate" [11].                                                                                                                                                                                                  |
| Carbon flux              | Rate of exchange (use/release) of carbon between the different parts composing the plant system (the photosynthetic parts, non-green tissues and the microorganisms associated with the growth substrates) [24].                                                                                                                                                                                                                                     |
| Bacterial community      | Analysis of the metabolic changes in the rhizospheric bacterial community was carried out by Irga et al. [24] to assess any contributions to VOC removal.                                                                                                                                                                                                                                                                                            |
| Transpiration rate       | Ratio of the mass of water transpired to the mass of dry matter produced.                                                                                                                                                                                                                                                                                                                                                                            |
| Growth index             | Changes in size of the plant or of its parts during the data collection period. It should be noted that the only source taking into consideration this parameter, also performed a qualitative assessment of the development of the root system taking into account root length, volume density and distribution [33].                                                                                                                               |
| Environmental conditions | Identifies the factors, external to the plant itself, that can affect its physical conditions as well as its exchange with the environment.                                                                                                                                                                                                                                                                                                          |
| Positioning in space     | Study reports on the precise location of the plant(s) within the testing space.                                                                                                                                                                                                                                                                                                                                                                      |
| Treatment before         | Actions of maintenance and/or support to plant development (repotting, fertilizers, watering, etc.) before the start of data collection.                                                                                                                                                                                                                                                                                                             |
| Treatment during         | Actions of maintenance and/or support to plant development (repotting, fertilizers, watering, etc.) during the time of the data collection.                                                                                                                                                                                                                                                                                                          |
| Air temperature          | Temperature conditions that the plants are exposed to (in °C or F).                                                                                                                                                                                                                                                                                                                                                                                  |
| Air movement             | Different measures describing the exchange and the movement of the air within the testing space. Mentioned aspects include: air freshness (mean age of the indoor air [17]), natural ventilation [30], air speed (air flow [11], air velocity [16,26]), turbulence (use of a chamber fan [22,27], air direction [16]), airtight conditions [27,29].                                                                                                  |
| Relative Humidity        | Humidity conditions that the plants are exposed to. Studies mostly report on RH (in %).                                                                                                                                                                                                                                                                                                                                                              |
| Light conditions         | Quality and characteristics of the light that the plants are exposed to. Mentioned aspects include light intensity [11,13,21,22,24,25,36,38], illuminance (lx) [13,28,37–39,42,44], duration of light (or photoperiod) [13,21,25,27,28], use of natural [13,31,35,36] or artificial [13,17,21,26,28,37,38,44] light source, photosynthetically active radiation (PAR) [21,22], photon fluence density (PFD) [27].                                    |
| Night monitoring         | Study reports that the plants were monitored during the night or in absence of light.                                                                                                                                                                                                                                                                                                                                                                |
| Seasonal monitoring      | Study reports that the plants were monitored during specific seasons or months.                                                                                                                                                                                                                                                                                                                                                                      |
| Lab environment          | Testing space with well-defined boundaries and narrowly controlled conditions. The category includes all types of lab-testing spaces from small testing chambers (boxes, jars, tubes, etc.) [18] to rooms with test subjects [39].                                                                                                                                                                                                                   |
| Real environment         | Testing space in an existing real-life indoor environment, with users performing their usual daily routines. The majority of the real-environment spaces tested are office spaces [17,36,40,41,43,44] or similar (photocopy center [30], a greenhouse used as office space [31], "room" not further defined but supposedly an office setting [13,42]). Other spaces tested include a classroom [35], indoor atriums [16,34], and private homes [41]. |

Table 2. Cont.

| Classification/Parameter | Definition/Notes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Focus                    | Main aim pursued in the study                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Air quality              | Plants' capacity to purify indoor air and absorb pollutants.                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Climate                  | Plants' impact on indoor climate in terms of temperature and humidity.                                                                                                                                                                                                                                                                                                                                                                                                                               |
| Acoustics                | Plants' impact on indoor acoustics. Although acoustic benefits of outdoor greenery have been shown in several studies, the acoustic impact of indoor greenery has been studied to a much lesser extent [34] (refer to Table 1).                                                                                                                                                                                                                                                                      |
| Mental health            | Plants' effects on human physiological and psychological health. Specific aspects considered in the reviewed literature refer to happiness [41], productivity [40], general wellbeing [31,41], cognitive performance [3], attitude [43], job satisfaction [43], stress (perceived stress, stress response) [38,40,42,44], psychological relaxation [39], emotions (or feelings) [42], novelty, perceived naturalness, preference, and environmental comfort [23,37], physiological response [31,37]. |

- “Daytime monitoring” (as opposed to “night monitoring”) was omitted as it is the understanding of the author that in the majority of the studies reviewed it is taken for granted that experiments on plants are carried out in light conditions—whether of natural or artificial source. This idea is supported by the fact that all sources reporting on night monitoring also reported on day monitoring, taking the day conditions as baseline. The choice of reporting only on studies taking into account night conditions mainly aims to highlight those studies that seemingly take into account a possible variation in performance due to changing environmental (light/heat) and internal (plant metabolic) conditions. It should, however, be noted that among the studies analyzed, a significant number do not specify day, night, or light conditions [16,23,33,40,41,43].
- “Seasonal monitoring” was during the first phase of the analysis further detailed, specifying during which season(s) the plants were studied. In the second phase of analysis of the tables, the author decided to highlight those studies that took into account any seasonal condition(s) that could have an impact on the results rather than providing more detail on specific seasons. It can, however, be noted that the most commonly mentioned seasons were winter and summer. More often than not, both winter and summer were monitored [16,17,31,32,36]—instead of only winter or summer [23,30,35].

### 3. Results

The outcome of the analysis of the plant parameters used in the selected papers is presented in the form of two tables (Table 2 and Table S1).

#### 3.1. Summary of the Plant-Related Parameters Described in the Reviewed Research

In the first phase, the selected papers were reviewed, and the parameters used to describe all aspects relating to the plants in the experiments listed. In the second phase, the parameters listed were organized according to similarities in the information (such as the same type of measurement, but with different metric systems) and the purpose (such as reporting on diverse actions such as repotting and watering, achieved with the same aim of supporting the plant's wellbeing). The resulting classification of parameters identified in the reviewed research is reported in Table 2.

A second table cross-checks the parameters identified in Table 2 and the regularity with which they are used and reported in the studies reviewed (Table S1, available in the Supplementary Materials).

#### 3.2. Considerations on the Plant-Related Parameters Reviewed

Table 2 and Table S1 highlight a number of inconsistencies and gaps in the reporting and management of the plant subjects across the studies reviewed. A summary of the main issues that were highlighted is given here according to the topic-specific subject areas.

### 3.2.1. Diversities across Studies

#### Plant Parameters Mentioned

The broad diversity of parameters observed reflects the complexity in the assessment of the plant material used. Radically different parameters were measured in studies with similar aims and little agreement seems to be reached concerning highly relevant reference parameters. As an example, among the 13 studies on air purification using potted plants in lab conditions [9–11,17,21–25,28–30,32], leaf area or density is not specified in five cases [9,10,17,23,32], the composition of the growth medium in four cases [10,21,28,32], the treatment given to the plants before the experiment in five cases [9,17,23,28,32], relative humidity (RH) conditions in four cases [10,24,29,30], and light conditions in six cases [9,10,23,29,30,32].

#### Plant Quantification Metrics

The most common method to quantify greenery in the studies appears to be counting the number of plants (16 out of 31 studies, about 52%).

The second preferred way is the leaf area or leaf density (with 14 out of 31 studies), which is mainly common in studies on IAQ (10 out of 14 studies on IAQ), although also a few studies on indoor climate [33,36], acoustics [18] and mental health [37] use a comparable metric.

The third preferred way to quantify greenery refers to the size of the plant, either the height (10 studies) or the size of the pot (10 studies). Three studies mention both [23,25,30] and four other studies refer to weight, out of which three used a combination with height or pot size [10,24,27].

Green walls are typically measured in square meters of plants (four out of six [13,16,26,34]).

Finally, it seems highly relevant to consider greenery in relation to the indoor space. In this case, the measure used is plants per square or cubic meter ( $\text{m}^2$ ,  $\text{m}^3$ ) [13,36].

#### Quantity of Greenery

The actual amount of greenery present in the experiments appears to vary with the scope of the study. Lab experiments that do not consider space for humans' coexistence with plants tend to maximize the amount of greenery within the experimental spaces. Measurements are made on single leaves (1 leaf/6  $\text{cm}^2$  of chamber) [22], single plants within an impedance tube [18], or plants of various sizes in boxes or jars of sizes ranging between 0.6 and 1000 L [9–11,21,24,25,27–29]. The quantity of plant material used drastically drops as experiments are scaled up to human-sized test chambers. In the plant-intensive scenarios, the number of plants used range from 1  $\text{m}^2$  plant/1  $\text{m}^3$  of lab space [26] to 1 plant/2.4  $\text{m}^2$  [13], 1 plant/5  $\text{m}^2$  [17], 1 pot/9.39  $\text{m}^2$  [30], 1 pot/15.4  $\text{m}^3$  [23], and 1 plant/18.25  $\text{m}^3$  [36]. In two cases, pot volume is compared to indoor space volume and quantities vary from 171  $\text{m}^3$  to 327  $\text{m}^3$  of the (estimated) indoor space/ $\text{m}^3$  of planted soil [35,39]. Experiments in real environments tendentially focus on relatively small amounts of plants in the order of 1 to 3 plants per desk [43,44].

The main difficulty in these cases was to estimate the indoor space. Some studies did not report the size of the indoor space, as in the work of Smith and Pitt [32], where the office was estimated to be around 3.000  $\text{m}^2$  based on the given floorplans, taking the green coverage down to around 1 plant/615  $\text{m}^2$ . In the work of Gunawardena and Steemers [16] and in Choi et al. [37] a quantitative comparison was not possible due to the difficulties in defining the spatial boundaries of the experimental environment. Finally, in three studies, no quantification parameter was mentioned at all [3,38,42], while in the case of De Lucia et al., the quantification was not relevant to the aim of the study (measuring the thermal transmittance of the green module).

### 3.2.2. Omitted Parameters and Information

#### Definition of Plant Subjects

The most common parameter mentioned in the category “qualification” is by far the plant species (25 studies out of 31). Nevertheless, as many as six studies (about 19% on the small sample of studies reviewed) do not account for the plant species involved in the study [3,16,35,38,41,43]. Yin et al. [3] do not define the material any further than “plants”, and Korpela et al. [41] only report the number of plants used. Ren and Tang [35] go as far as mentioning a “small shrub”, and referring to conditions “with/without plants”.

The second most common parameter mentioned relates to the type of growing medium provided for the plants (12 studies). However, out of these, as many as nine focus on IAQ [11,17,22–26,29,30], where the growing medium is likely more important in terms of the absorption of air pollutants than of plant growth quality.

#### Plant Health and Conditions

In a number of studies, little or no information is given on the plant material while there is a clearer focus on the experimental conditions [38,39,42]. Parameters indicating plant health are relatively few (“growing index” [33], photosynthetic rate and/or chlorophyll concentration [11,22,33,36]) and generic (“plant health” [16,28,44]). Only 11 studies mention the treatment given to the plants before and/or during the experiment.

Parameters indicating plant maturity (biological stage of the development of the plant [9,10,22,25,30,36]) and metabolic phases (10 studies report on night monitoring and seven on seasonal monitoring conditions) are also relatively scarce.

Parameters indicating environmental conditions are slightly more common but are still mentioned only in a slight majority of the studies: light conditions (19 studies), air temperature (19 studies), relative humidity (18 studies) and air movement (eight studies).

#### Plant Performance

Relevant parameters for the specific aim of the study are sometimes not considered. For instance, in 5 out of 15 studies dealing with real-life conditions, the positioning of the plants within the space is not mentioned [3,13,35,41,42]. Out of the nine studies focusing on indoor climate conditions, only one measured plant transpiration [36]. Among the 17 studies on IAQ, only one analyzed carbon flux and changes in the bacterial community [24].

### 3.2.3. Convenience Prioritized over Plant Physiology

Indoor spaces integrating plants show systematic limits in reproducing the natural conditions for plants.

- Plants have limited and individual space for growth. In total, 22 out of 31 studies use planting systems with limited space for root growth (potted or hydroculture).
- Plants are largely introduced as individuals rather than in groups. Combinations of more plants growing in close proximity are rarely considered. Out of the studies reviewed, only five consider assessing different plant combinations [13,18,31–33]. In fact, many studies seem to focus on the effects of individual plants [18,22,44], which is especially the case in many IAQ studies [9–11,21,24,27–30].

## 4. Discussion

### 4.1. Summary and Research Gap

Research on the effects of introducing greenery in indoor environments has, in the last 30 years, made an important effort to map the cause and effects of the introduction of single plants of different plant species. No major breakthroughs have, however, been made since the NASA clean air study [9], which was amongst the first to address the topic. Therefore, it is the aim of this study to take a fresh look at the existing research in order to suggest a new approach. Instead of focusing on the main aim of the experimental research reviewed—assessing how plants can enhance the environmental quality of the indoor environment—this study has attempted to assess the relevance that plants are really given

within the studies. To the knowledge of the author, no other study has previously been reported with a similar intent.

#### 4.2. Main Findings

A brief exploratory review was carried out using 31 cases reporting on experimental research on plants in indoor environments, with varying aims from indoor air quality to acoustic, climatic and mental health.

The results of the review highlighted that although the plants are the primary or the secondary study subjects, they are often partially described and are not exposed to their optimal conditions. The shortcomings highlighted by the analysis of Table 2 and Table S1 can be grouped into three major thematic areas.

##### 4.2.1. Diversities across Studies

###### Plant Parameters Mentioned

From the diversity of parameters observed in the studies, no protocol or scientific agreement seems to have been established concerning the minimum number of parameters to take into account. Radically different parameters are measured in studies with similar aims, making the comparison of methods and results very difficult.

###### Plant Quantification Metrics

The analysis highlighted a broad diversity in the metrics used. This result is in accordance with a number of other studies which have also highlighted inconsistent metrics: the metrics were found to be either too different to enable comparisons between studies [14] or difficult to scale up and contextualize the results in other scenarios (in IAQ studies, suggested measures are the mass of the pollutant removed per hour per plant [8], and clean air delivery rate CADR in  $\text{m}^3/\text{h}$  [14]).

Counting the number of plants was found to be the preferred way to quantify greenery (16 out of 31 studies). Counting plants can, however, become controversial and misleading as a metric as reporting the number of individuals alone omits many aspects that are important. Plants can differ greatly between species, but also between individuals: How should plants with multiple stems be counted? Can a 50 cm and a 500 cm *Ficus elastica* be equally counted?

Measuring plant size alone (plant height or size of the pot) equally has its limits as the size alone is no reliable indication of plant performance. A plant might be tall but have very low leaf coverage for instance. The same limits apply to systems measuring plant coverage in square meters of plants (green walls).

Thus far, for the effects that primarily depend on the plant leaves, the single quantification metric that was found to reliably measure plant performance was the leaf area or leaf density. However, as pointed out, the quantification of greenery always needs to be related to the aim of the study as different plant qualities might be relevant to the desired effects. At best, more parameters should be combined or referred to so as to give a more complete picture.

Finally, the selected plant metric should always be put in relation to the size of the indoor space it refers to. Many case studies, and especially those performed in real environments, lack proper information concerning the size of the space studied.

###### Quantity of Greenery

It seems intuitive to expect a direct relationship between the quantity of greenery and the magnitude of the effects. The number of plants has in fact been linked to effects as indoor air purification,  $\text{CO}_2$  levels [23], indoor humidity and temperature [23]. According to Bringslimark et al. [40], the number of indoor plants in the direct proximity of users has a small but statistically reliable impact on sick leave and productivity.

The actual amount of greenery present in the experiments appears to vary with the scope of the study. Lab experiments not including any users have the tendency to maximize

the amount of greenery present within the experimental spaces. The quantity of plant material used, however, drastically drops as experiments are scaled up to human-sized test chambers, whereas experiments in real environments tendentially focus on relatively small numbers of plants. These results are supported by the considerations made by other authors pointing out how the necessary number of plants to emulate the effects obtained in the test chambers exceed by far the amount that would be reasonable in an indoor environment [8,14].

#### 4.2.2. Omitted Parameters and Information

Omissions can be partially explained with the study background of the authors not being adequately informed in terms of plant physiology. The analysis of sources (Figure 2a) has highlighted that 24% of the authors probably have a background in plant science studies, and an additional 24% can be considered if the environmental sciences are taken into account. This leaves 52% of the authors having a background in other areas of study.

##### Definition of Plant Subjects

The broad diversity of plants and their connected parameters complicate the assessment of greenery, so aspects such as species, size, health, etc., are highly relevant to consider and to combine. In this category, three main types of omissions were noticed.

- Studies focused surprisingly little on plants, as in the cases of Yin et al. [3], Korpela, De Bloom [41] and Ren and Tang [35].
- Plants are an important part of the study but there are important omissions concerning the plant parameters reported, as is the case of Gunawardena and Steemers [16], who mention many plant parameters but not the species.
- Plant parameters are used as indicators for other factors. An example of this is the “growing medium”, which is mentioned by 10 studies, out of which seven focus on IAQ [11,17,22,23,25,29,30], indicating that the authors might have in mind the potential absorption of air pollutants through the soil rather than accounting for the plants’ conditions. This supposition could be supported by the overall scarcity of other parameters indicating general plant health.

##### Plant Health and Conditions

The fact that plants’ performances and impacts on the indoor environment strongly depend on their inner health conditions [32], as well as the environmental conditions surrounding them, seems obvious. Still, factors indicating plant health and physiological conditions are relatively scarce. Many studies fail to specify when experiments are exclusively carried out in day conditions. It may seem obvious that the plants are primarily analyzed during their metabolically more active period of the day (in other words, when daylight is available). However, equally important pieces of information—such as the stage of maturation of the plants—are often disregarded.

Plants are, in many studies, tested as individuals rather than as a system of individuals that support each other’s functions, disregarding any potential implications of their association. This is the case of many plant health-related aspects, which are, in reality, much more complex than what can be represented through the simple parameters reported. As highlighted by Döring et al. [45], health does not only vary between individuals, but health and disease are dynamic concepts which change over time, there are geographical patterns of pathogen occurrence, and pathogens can also develop resistance to treatment.

##### Plant Performance

All the reviewed studies focus on the effects of introducing plants in indoor environments. Nevertheless, many studies account for alarmingly few relevant plant performance parameters. Specifically, plant parameters that are relevant to the effects the plant has on the environment need to be systematically used and combined with indoor environmental measurements that are crucial for plant performance such as ventilation rates, behavior of

air distribution [8], humidity, CO<sub>2</sub> levels, light intensity and wavelengths [22,24]. Adequate lighting conditions can in fact be problematic in many indoor spaces. Although indoor plants are typically “shade plants” able to adapt to lower light conditions, the range of shade tolerances among indoor species still need to be quantified according to Burchett [22].

Indicators of plants’ metabolic capacity and plant transpiration are the main indicators that need further implementation in the research in this field. The nitrogen content is another factor that has been found to be of significance in terms of plant metabolism. According to Reich et al. [46], nitrogen content is directly related to metabolism rate, respiration and carbon dioxide emissions, regardless of plant size.

#### 4.2.3. Convenience Prioritized over Plant Physiology

In natural environments, plants are intimately associated with other plants [47]. Plants are, for instance, known to communicate and interact extensively with symbionts through their roots and the associated microbial communities. This enables them to thrive and to protect themselves against harmful biotic and abiotic factors [48], with a great impact on plant health, resilience and development [20,49]. Despite this, plants are systematically limited in their growth and communication, as a large number of studies (20 out of 31 studies) use pots, cutting the plants off from any potential plant–plant root communication.

Interior environments are also limited in terms of biodiversity. The combination of more plants growing in close proximity has been shown to recreate multi-layered foliage canopies (a vertical stratification of vegetation growing at different heights) able to partially sustain and regulate healthy self-hydrating conditions [16] as well as the removal efficiency of VOCs [29]. Still, the review highlighted how plants are mostly studied in terms of their individual performances rather than as a system.

The reasons behind these limitations could be of two types:

- Indoor environments are spaces built primarily for humans and naturally prioritize human convenience. For economical as well as for practical reasons, plants are “guests” in indoor spaces, kept primarily for aesthetic reasons. In other terms, plants and humans potentially clash in terms of needs: plants take up valuable space, light, can bring unwanted water damage and pests. Hence, plants are introduced as individual objects, in limited numbers and in terms that are practical to humans. As a consequence, buildings are also not built with human–plant coexistence in mind: plant soil and space are limited, buildings are not dimensioned to carry and distribute the weights or planned to manage complex watering systems.
- The scientific study of the effect of plants requires, in the first step, to study the effects of single plants of different species and in different conditions. In that scenario, the greater complexity of which the plants are part of is not negated, but parts of it are rather extrapolated to enable a more focused assessment. This means that any results need to be re-contextualized, highlighting that the same outcomes might have important variations if the plants are studied within a system of interdependent plants. In the present review, however, none of the studies mentioned any plant-system scenario which could support this supposition.

#### 4.3. Hypothesis

The hypothesis put forward by the author is that the results indicate the existence of a strongly anthropocentric mindset in the field, which tends to disregard important aspects such as plant subjects’ wellbeing and operational logic, with the risk of affecting the reliability of the results as well as their interpretation. A number of aspects that have emerged in the analysis support the hypothesis.

In the future, if plants are to be used for more than their aesthetical quality, to contribute to indoor environmental regulation and human health [14], their conditions need to be upgraded to enable proper performance. This upgrading strongly concerns the research in the field, which needs to observe the plants in their best possible conditions to be able

to effectively and qualitatively inform on the design of indoor green spaces. Indoor plant systems need to be rethought in terms of:

- The quantity of plants, maximizing the amount of greenery that can be introduced.
- The type of plants, introducing wider selections of species and mixing different plant heights. Focus should be put on species that can cohabitate together, compensating each other's needs, recreating the basic forms of symbiosis.
- Potting systems, enabling larger growth area and inter-root communication between plants.
- Biodiversity, introducing selected microbiota that benefit the plants as well as the environmental quality [22].

#### 4.4. Limitations

The main limitation of this study is without doubt the limited number of studies reviewed. The selected 31 studies, even if highly representative of the methods and mindset adopted in their specific field of study, are not a sample large enough to enable a generalization of the findings.

Limitations to the selection process of the reviewed studies are of three main types: (i) literature research through keywords only, (ii) the accessibility of the identified studies, and (iii) possible selection bias:

- The initial search for literature based only on the selected keywords is necessarily limited. A thorough review needs to also extend the search to relevant sources cited by the papers identified.
- A large majority of the studies selected were available online through different open access modes (open access publishing or availability through research platforms such as ResearchGate). Although this was not a selection criterion, the assortment was certainly impacted by the availability of these studies in comparison to others that are potentially as relevant.
- The definition of selection criteria and procedures adopted (refer to Section 2.1) aims to ensure the transparency and the impartiality of the literature selection. However, due to the restricted number of studies selected and the work being carried out by one author alone, it is difficult to completely exclude the occurrence of a selection bias. Any shortcomings from this point of view should be corrected as a more thorough review is undertaken.

Other factors to consider, that potentially influence the results include:

- The nationality and scientific background of the authors of the studies (highlighted in Figure 2a,b), which can highlight specific schools of thought and mindsets.
- The language in which the results are published. The studies selected were all (but two) published in English, an additional factor which might reinforce the recurrence of specific schools of thought. One of the studies was published in German language [31] and another in Korean [36]. The latter one was translated by the author using an open-source translation tool (google translate), being aware of the high probability of linguistic inaccuracies.

It is, therefore, clear that the results presented are an exploratory attempt to identify major and common inconsistencies, indicating new paths of research, and any generalization based on the findings should be made with caution.

#### 4.5. Future Directions

As anticipated, this paper can only be considered as a first step within a longer research process in which the use and study of plants in indoor environments is completely rethought.

First of all, a thorough review of the available studies involving the use of plants in indoor contexts is necessary to enable a proper generalization of the results, confirming or

refuting the hypothesis put forward. Within this context, further efforts will be needed to map the patterns and explain the reasons behind the systematic gaps.

If the hypothesis is confirmed, the results advanced in the existing research on indoor plants will need to be re-interpreted and put into the new perspective, involving experiments more oriented towards plants' needs and functioning. This involves developing new experimental protocols, establishing reliable aim-specific plant parameters and updating relevant studies using upgraded plant conditions.

One main research direction which seems promising involves the systematization of a multitude of species—of plant as well as of animal origins—to effectively use indoor spaces as ecosystems, as opposed to the individual plant–human–building environment approach adopted so far. The theoretical bases for this type of research can be partially found in attempts performing a microbiological reading of the built environment [50] and in the use of bio-informed designs [51].

## 5. Conclusions

This study is the first attempt to read the existing research on the use of plants in indoor environments from a different perspective, that of the plants, and challenge scientists' current line of thought. In total, 31 papers reporting on experimental research using plants in indoor environments were selected and analyzed, listing and categorizing all parameters that seemed significant for the description and the assessment of the plants used.

The analysis of the plant-related parameters highlighted major inconsistencies between studies with similar intents, as well as a diffused lack of highly relevant information concerning the plants and their environmental conditions. The shortcomings highlighted by the analyses of Table 2 and Table S1 can be grouped into three major thematic areas: (i) diversity in the parameters across studies; (ii) lack of parameters—systematic mistakes/omissions in the data; (iii) anthropocentric logic.

The hypothesis suggested by the author, on the basis of the results, is that the existing research involving plants in indoor environments is strongly characterized by an anthropocentric mindset. This specific perspective tends to disregard important aspects of the plant subjects' wellbeing and operational logic. On the one hand, the lack of interest and focus on plants' physiological needs and functioning substantially impacts the whole design of the experiments. On the other, the information gaps regarding the plant subjects' risk affects the reliability of the results and their interpretation.

The results of this paper indicate possible research directions. Still, a more complete systematic review is needed to confirm that the gaps highlighted are systematic. Future work needs to aim at developing new experimental protocols within a more plant-oriented perspective, including listing topic-relevant plant parameters. Plants in indoor environments need to be interpreted as a network of individuals working within a symbiotic system, effectively understanding and treating indoor environments as specific ecosystems where plants, microorganisms and humans coexist and interact.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/architecture1020008/s1>, Table S1: Plant-related parameters reported on in the reviewed research.

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