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REVIEW ARTICLE

The basic roles of indoor plants in human health and comfort

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Abstract
Humans have a close relationship with nature, and so integrating the nature world into indoor space could effectively increase people's engagement with nature, and this in turn may benefit their health and comfort. Since people spend 80–90% of their time indoors, the indoor environment is very important for their health. Indoor plants are part of natural indoor environment, but their effect on the indoor environment and on humans has not been quantified. This review provides a comprehensive summary of the role and importance of indoor plants in human health and comfort according to the following four criteria: photosynthesis; transpiration; psychological effects; and purification. Photosynthesis and transpiration are important mechanisms for plants, and the basic functions maintaining the carbon and oxygen cycles in nature. Above all have potential inspiration to human's activities that people often ignored, for example, the application of solar panel, artificial photosynthesis, and green roof/facades were motivated by those functions. Indoor plants have also been shown to have indirect unconscious psychological effect on task performance, health, and levels of stress. Indoor plants can act as indoor air purifiers, they are an effective way to reduce pollutants indoor to reduce human exposure, and have been widely studied in this regard. Indoor plants have potential applications in other fields, including sensing, solar energy, acoustic, and people's health and comfort. Making full use of various effects in plants benefit human health and comfort.

Keywords Indoor plants · Photosynthesis · Transpiration · Psychological effect · Purification · Health

Introduction

Humans have a close relationship with the natural world. Interacting with nature is important for both increasing the quality of life and delivering a range of measurable benefits to people (Adachi et al. 2000; Dijkstra et al. 2008; Pretty 2004), including psychological benefits and cognitive performance (Keniger et al. 2013). In recent articles, the health effects of exposure to the outdoor nature were discussed in detail (Bernstein et al. 2004; Kampa and Castanas 2008; Deng et al. 2015a). However, the role of the indoor natural environment has received relatively little attention compared to the number of studies on the role of the outdoor. Since urban people spent 80–90% of their lives indoors (in both residential and public space), and longer for children, the elderly, and the sick and disable (Deng et al. 2018b; Pandey et al. 1989; Rinne et al. 2006), there is a growing public awareness regarding the risks associated with poor indoor environment. Indoor environment is a major contributor to personal exposure to many air pollutants (Franklin 2007). The indoor natural environment is therefore very important to human health and comfort (Claudio 2011).

Indoor plants exist as part of the three-dimensional environment and interact with human in many aspects. Photosynthesis is the process by which a plant converts carbon dioxide (CO_2), light, and water into energy and releasing oxygen (O_2) as a by-product. O_2 is essential for other organisms to thrive, these processes forming the earth's carton and oxygen cycles (Messinger and Renger 2008). Negative air ions (NAIs) produced during photosynthesis are good for people's health (Yan et al. 2015). Photosynthesis and transpiration processes are important for plants (Bot 2001), above all had potential inspiration to human's activities that people often ignored (Benniston and Harriman 2008). Based on the photosynthesis principle, people have constructed artificial systems

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to improve solar energy conversion efficiencies in order to develop new clean energy (House et al. 2015; Kalyanasundaram and Graetzel 2010). Transpiration is the process relying on water travels from the root to the leaves of plants where it turns into water vapor and is released to the atmosphere. This property of plants makes them useful for regulating relative humidity indoor (Kichah et al. 2012). Plants also have the potential for thermal regulation, for example Jim 2014 found that the Peanut roof can cool the near-ground air whereas the Sedum can warm it.

It has been observed that engaging with the outdoor natural environment has significant positive physiological and psychological health benefits. This suggests that integrating the natural environment into indoor space can be an effective way to extend engagement with nature and benefit people (task performance, health and stress) (Bringslimark et al. 2009; Shibata and Suzuki 2002).

The most common types of indoor air pollutants such as particulate matter (dust, smoke, and biomass), bioaerosols (molds, spores), and gaseous contaminants (nitrogen dioxide, carbon monoxide, sulfur dioxide, ozone, formaldehyde, and volatile organic compounds) derived from building product emissions, human activity indoor, and infiltration of outdoor air are important contributors to poor indoor air quality (IAQ), adversely impacting indoor occupants by causing discomfort, as well as acute and chronic disease (Aydogan and Montoya 2011; Deng et al. 2018a; Van Loy et al. 2001; Wolkoff and Nielsen 2001). Detailed indoor pollutants and emission sources were summarized (Jones 1999). Indoor pollutants act as respiratory irritants, toxicants, and adjuvants or carriers of allergens (Bernstein et al. 2008). Postnatal indoor exposure was associated with childhood otitis media (Deng et al. 2017). "Sick building syndrome", manifested by ocular, nasal, and cutaneous irritations; allergies; respiratory dysfunction; headache; fatigue; and metabolic disorders, is one of the most typical indicators of poor IAQ (Lu et al. 2016).

Phytoremediation is a novel strategy to effectively remove pollutants using plants. Some researchers has reviewed using plants to remediate organic pollutant soil (Ren et al. 2018a, 2018b) and heavy metal pollution water (Bello et al. 2018). Many studies have used plants as a biological filter to purify indoor air since this process is environmentally friendly and is low cost (Darlington et al. 2001). Deng et al. 2015b reported that early life (in utero and first year) exposure to indoor renovation were associated with the subsequent development of childhood asthma. The studies (Mishra 2003; Mumford et al. 1987; Smith et al. 2000) on exposure to indoor air pollution from household biomass fuels were rather consistent, and showed a very significant increase of the risk for exposure of young children (respiratory infection and acute respiratory illness), women (respiratory illnesses and lung cancer), and the elderly (asthma) compared with those living in households using cleaner fuels or being otherwise less exposed. The indoor environment therefore is very important to human health, and one of the methods in making a healthier indoor environment is the use of indoor plants.

Indoor plants not only play a significant role in the elimination of indoor air pollutants, but also contribute to improving the indoor environment, providing a positive psychological effect on individuals and promoting health and comfort (Fjeld et al. 1998; Han 2009; Xu et al. 2011). This review provides an overall summary of the four roles of indoor plants for human health and comfort (Fig. 1), while also looking at the probability of development and application in the future.

Progression in the research of indoor plants

Photosynthesis

Natural photosynthesis, using light as the energy source, is the process of fixing CO_2 in the form of carbohydrate and releasing O_2.

Since the solar energy conversion efficiency in natural photosynthesis is very low, it is necessary to improve net photosynthesis for the purpose of energy need and releasing O_2 (Bot 2001). For plants, the net photosynthesis is affected by many factors, such as light, CO_2, temperature, leaf area size, mineral elements, and water (Bergstrand and Schussler 2013; Garland et al. 2012; Torpy et al. 2014).

It is important to provide the appropriate light environment for indoor plants. The light needed by many plants need to be above the light compensation point (zero net photosynthesis) so as to maintain proper O_2 levels in the air. The photosynthesis-light response curve is frequently used to study the overall photosynthesis performance of plants (Nemali and van Iersel 2004; Terashima and Saeki 1985). Different light spectra have different effects on photosynthesis. The most commonly used radiation source in plant-growing facilities is the light-emitting diodes (LEDs) (Ignatius et al. 1991). LEDs of specific wavelengths can be used to provide for the different needs of plants (Nemali and van Iersel 2004; Oh et al. 2011). Both red light (625–700 nm) and blue light (425–490 nm) were the basal component of light spectra for green plants' growing need. It have been proved that the combination of red and blue lights should be favorable to increase photosynthesis (Bergstrand and Schussler 2013; Hogewoning et al. 2010; Kim et al. 2004; Liu et al. 2011). These studies mainly focused on the proper light to improve biomass in terms of providing food yield serving human. On the other hand, it suggested that light wavelength (400–500 nm and 600–700 nm) would meet the nutritional needs of plants and maximal O_2 release under indoor lighting conditions (100–500 lx) to benefit human health and comfort.

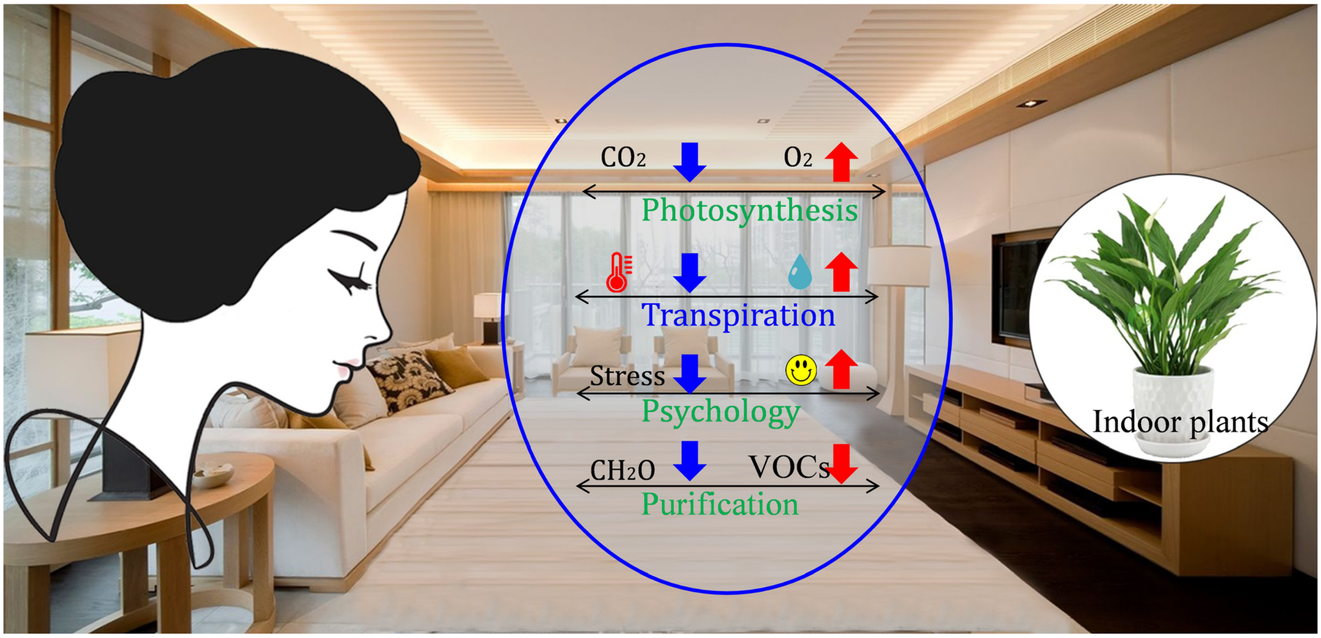

Fig. 1 The diagram about basic roles of indoor plants in human health and comfort

Elevated CO_2 can increase in net photosynthesis, resulting in an increase in the release of O_2 (Cure and Acock 1986). Photosynthesis varies with light quality and CO_2 concentration in plants cells (Zeiger and Field 1982). That is, the stronger the light, the higher the net photosynthesis rate, and the lower concentration of CO_2 in the cells (Jarvis and Morison 1981; Oh et al. 2011). Installations of indoor plants could be designed to remove a proportion of indoor CO_2 and to release O_2 according to the optimal choice of living environment (Torpy et al. 2014). Sinae et al. 2010 discovered that optimum environmental control would be required to increase the elimination capacity of indoor CO_2. Pennisi and van Iersel 2012 integrated the C fixed by the indoor plants with the amount of the CO_2 exhaled by a single person, and found that it would take 400 plants to eliminate CO_2 exhaled by one person. The larger the leaf area, the higher the CO_2 elimination by indoor plants. Irga et al. 2013 estimated that it would require 57 m^2 of leaf area to balance the respiration of a single occupant in an average sized office (43 ± 2 m^3) without ventilation. found that it would require 240 plants to absorb 13% of the CO_2 generated by one person. Studies using plants to counteract the CO_2 release by human were differed by different aspects (leaf area and number).

The optimal temperature for photosynthesis is influenced mainly by the growing environment (Medlyn et al. 2002). A decrease in the net photosynthesis rate of *Quercus suber* occurred when the temperature increased above 30 °C (Tenhunen et al. 1984). Indoor plants generally could not achieve maximum photosynthesis under indoor condition (24 °C). On the other hand, it may reduce whole plant photosynthesis by limiting the evaporative surface area. The maximal density converted to leaf area per 1 m^3 of plant volume to allow application in real space was 18,000 cm^2 m^{-3} for peace lily and areca palm, and 12,000 cm^2 m^{-3} for weeping fig (Oh et al. 2011). Water is necessary for photosynthesis. The rate of photosynthesis in both C_3 and C_4 plants decreased as their relative water content and water potential decreased (Silva et al. 2010). Water stress strongly affects photosynthesis which in turn affects the growth and survival of plant species growing in semi-arid climate (Chaves et al. 2002; Tezara et al. 1999). It is estimated that the water use efficiency (net photosynthesis rate/transpiration rate) of carnation plants will increase by 40–50% over the next 50 years due to the projected increase in the global CO_2 concentration (Enoch and Hurd 1979).

While photosynthesis releases O_2, the photoelectric effect (photosynthesis in leaf tips) can produce numerous negative air ions (NAIs). NAIs play a very important role in absorbing dust, cleaning the air, and improving the environment and human health (Perez et al. 2013; Wu and Lee 2004; Yan et al. 2015). Shiue et al. 2011 have found that NAIs can be used to efficiently control ultrafine aerosol pollutants in cleanrooms. Results have shown that some pot plants could generate NAIs (Tikhonov et al. 2004). However, a very small amount of NAIs are produced by plants under indoor condition. Using plants to produce fresh air abundant of NAIs is a big challenge ahead. Superoxide ($O_2^{\cdot -}$) is the main NAI and is more stable than other ions (Wu and Lee 2004). In the absence of photosynthesis, animals would deplete the atmosphere of O_2. O_2 is essential to life, and low oxygen levels lead to hypoxia which adversely affects human health, such as cognitive dysfunction (Browne et al. 2003; Titus et al. 2007), sleep deprivation (Blunden and Beebe 2006), and stunted nerve development (Ruijtenbeek et al. 2003). Since indoor plants absorb CO_2 and release O_2, they are the perfect complement to humans when it comes to gases. Using indoor plants to release more O_2 and NAIs would appear to benefit human health and comfort. Further research is needed to evaluate how to optimize this relationship.

Mankind is facing a major challenge to find new ways to create clean and renewable energy to cope with the increasing demand. Using artificial photosynthesis mechanisms to generate energy is one answer to this challenge (Ringsmuth et al. 2016; Wilhelm and Selmar 2011). Inspired by natural photosynthesis, artificial photosynthesis resulted in the development of new technologies to mimic green plants by driving solar powered reactions to split water into H_2 and O_2 or to convert CO_2 into a carbon fuel. Jeon et al. 2015 developed a highly efficient solar energy to fuel conversion device using CO_2 and water.

It is suggested that controlling the main factors affected plant photosynthesis (temperature: 21–25 °C; light flux: 100–500 lx; light wavelength: 400–700 nm), which would be remarkable for reducing CO_2 for purposes of slowing global warming, and keeping C and O and other elements cycling in balance in nature, eventually contribute to human health and comfort.

Transpiration

Transpiration has a big impact on the energy and mass balance inside an enclosed environment. Radioactive and convective transfers are the main exchange processes directly influencing plant production through photosynthesis and transpiration (Roy et al. 2002). Parts of the absorbed solar energy are transformed into latent heat through transpiration because the plants tried to maintain a constant moderate temperature inside the canopy (Boulard and Wang 2000). The ability to convert the absorbed energy into latent heat depends on the evolution of transpiration during the ontogeny and metabolism of plants. The efficiency of the transpiration process depends on the radiation, vapor pressure deficit (VPD), temperature, humidity, the type of plant, and other factors (Kichah et al. 2012; Mahajan et al. 2008; Montero et al. 2001). Wang and Boulard 2000 indicated that internal solar radiation, VDP, and convection were main factors influencing transpiration, with internal solar radiation being the most important of these. The diurnal canopy transpiration rate of plants increases with solar radiation and increases linearly with the VPD (Medrano et al. 2005). A low leaf temperature and high relative humidity leads to reduced transpiration (Mahajan et al. 2008). Transpiration can also decrease with increasing CO_2 (Reddy et al. 1995). Zhang et al. 2002 observed that transpiration decreased by 30% when the atmospheric CO_2 concentration doubles. Transpiration, as a controller of Cadmium accumulation in shoots, has been investigated (Salt et al. 1995; Van der Vliet et al. 2007). Stomatal pores in the leaf surface are able to progressively close thus decreasing the conduction of water vapor, and slowing transpiration (Tezara et al. 1999). The temperature of the leaves when the stomata were open was about 5 °C lower than when the stomata were forced to remain closed (Cook et al. 1964). The transpiration process can use up to 70% of the solar radiation absorbed by the greenhouse plants during summer which was improved by considering the plant stomatal resistance (Wang and Boulard 2000).

Green plant transpiration is one of the natural ways to cool (Seginer 1994). When the absorbed radiative energy is less than the energy required for transpiration, the temperature of the plant will drop thus cooling the ambient temperature (Kichah et al. 2012; Mangone et al. 2014). A high transpiration rate is responsible for the fact that the leaves were cooler than the surrounding air (Montero et al. 2001). Evidence suggests that during the day, the air temperature under a tree is lower than in the surrounding space, while the nocturnal air temperature beneath a tree can be slightly higher than the surrounding area (Bowler et al. 2010). Green facades on building can provide cooling through evapotranspiration to reduce the heat load of the building (Kovats and Hajat 2008). A maximum drop of 6 °C was observed for a building with a living wall in warmer condition (Fernández-Cañero et al. 2012). In addition, thick vines or ivy covered wall can reduce the peak-cooling load by 28% on a hot day, while increasing the air moisture content by 10–20% (Wang and Wang 1999). Another research has shown that the cooling effects depended mainly on shading, and that a smaller proportion was due to transpiration (Hoelscher et al. 2016).

A complete understanding of transpiration in indoor plants would enable more precise water management and the ability to better adapt to changes in the environment. Like photosynthesis, previous studies about transpiration focus on how to optimize the energy consumption of the whole system and the use of water. The potential transpiration of plants should also be noted. Indoor plants not only regulate indoor humility and temperature, but also reducing building energy consumption. Taking advantage of transpiration in indoor plants to regulate air temperature and humidity is a promising application, as it could reduce the amount of energy consumed for air conditioning. Since the ability to reduce temperature is limited, using transpiration in practice as an air conditioning system will require a lot more effort. It is important to consider the plant cooling capacity, species, and collocation.

Psychological effect

The practice of cultivating plants indoors has a long history. The presence of living things seemed to help people feel secure and relaxed and to increase their levels of positive energy; however, there is very little understanding of these psychological effects. Table 1 provides an overview of studies into the

Table 1 Overview of the reviewed studies with regard to study design, subjects, independent variables, outcome measures, and results as reported of indoor plants on psychological effects

References	Country	Study design	Subjects	Independent variables	Outcome measures	Effects of plants as reported
Adachi et al. 2000	Japan	Watch a video and questionnaires	53 volunteer students	Floral display, foliage display	Mood scores	Floral display had positive effects on human emotions; foliage display tended to have a positive effect on clear headedness, but increase in annoyance
Bringslimark et al. 2007	Norway	Anonymous e-mail questionnaire	385 office workers	Indoor plants	Perceived stress; sick leave; productivity	Beneficial effects on psychophysiological stress, task performance, and symptoms of ill health
Chang and Chen 2005	Taiwan, China	Psychophysiological laboratory and state anxiety Inventory (20 questions)	38 volunteer students	Window view and indoor plants	Psychophysiological response (electromyo graphy; electroencephalography; blood volume pulse) and state anxiety inventory.	Less nervous or anxious
Dijkstra et al. 2008	Netherlands	Laboratory experiments and questionnaire	77 volunteers of students in hospital room	Indoor plants	Perceived attractiveness; stress	Reduce feelings of stress through the perceived attractiveness of the room
Dravigne et al. 2008	USA	Job satisfaction survey	425 office workers	Interior plants or window views of exterior green spaces	Environmental preferences; elements of job satisfaction and overall life quality; demographic and work environment questions	Feel better performance, higher overall quality-of-life; male feel satisfied. Gender differences
Evensen et al. 2015	Norway	1-h work session with one of three interior conditions: live plants, inanimate objects and control	85 participants	Live plants, inanimate objects	Restorative effects of plants	Provide a restorative potential at the computer workstation
Fjeld et al. 1998	Norway	Task performance and questionnaire	51 office workers	Indoor foliage plants	Health and discomfort symptoms	Significant reduction neuropsychological symptoms and mucous membrane symptoms; improvement in health and a reduction in symptoms of discomfort
Fjeld 2000	Norway	Questionnaire	51 office workers	Foliage plants or a combination of foliage plants and full--spectrum fluorescent lamps	Self-reported health and discomfort complaints	Affect productivity, work satisfaction, or even sick-leave absence
Guéguen 2012	France	A survey in a room without windows	60 undergraduates	Dead indoor plants	Provided demographic and report their attitudes about varied topic	Physical cues strengthen belief in global warming
Han 2009	Taiwan, China	Quasi-experimental approach	76 junior high school students in classroom	Leafy Indoor plants	Psychology, physiology, and behavior	Immediately and significantly stronger feelings of preference, comfort, and friendliness
Larsen et al. 1998	USA	Task and questionnaire	81 participants	Indoor foliage plant density	Production task	Increase the comfort and attractiveness of office environment; beneficial effects on perceived

Table 1 (continued)

References	Country	Study design	Subjects	Independent variables	Outcome measures	Effects of plants as reported
						attractiveness; but decrease the production
Lohr and Pearson-Mims 1996	USA	Computer laboratory	96 undergraduates	Foliage plants to a windowless work place	Computer productivity test; blood pressure and emotions	More productive; less stressed; more attentive
Park and Mattson 2009	USA	Test and questionnaire	90 patients recovering from a hemorrhoidectomy	Viewing indoor plants and flowers	Ratings of pain intensity, pain distress, anxiety and fatigue, the State–Trait Anxiety Inventory Form Y-1, the Environmental Assessment Scale, and the Patient's Room Satisfaction	Brighten up the room environment, reduced stress, and also convey positive impressions of hospital employees caring for patients
Raanaas et al. 2011	USA	Laboratory experiment	34 students	Indoor plants (flowering and foliage)	Attention capacity using a reading span test	Improve the performance; affect cognitive performance
Shibata and Suzuki 2004	Japan	Task and the questionnaire (nine)	90 undergraduates	Indoor plants	Mood, the tasks, and the indoor environment	Better mood; task performance of female participants was enhanced; females have a high reactivity to the affective source
Shibata and Suzuki 2002	Japan	Task and the questionnaire	Undergraduate students	Indoor foliage plants	Task score;task performance and mood	Better mood; creative work positively
Shibata and Suzuki 2001	Japan	Task performance and questionnaire (14 questions)	70 undergraduates	Indoor foliage plants	Participants' task performance; fatigue; mood	Restorative effect on fatigue in task performance, but no effects on mood and fatigue evaluation
Shoemaker et al. 1992	Italy	Experiment in 9th and 11th floors of the building and questionnaire (23)	Employees in the building	Indoor plants	Opinions and attitudes of workers and job satisfaction	Favorable attitude; made it a more desirable place to work; improving air quality

Note: The references rank in alphabetical order of first authors' name

psychological effects of indoor plants, according to study design, subjects, independent variables, outcome measures, and effect of plants as reported. Most participants were student volunteers and the rest were office workers in office buildings and patients in hospitals.

Research design varied for different situations and usually incorporated questionnaire, an experiment, or both. Almost all of the studies included a plant-free control condition, but otherwise varied considerably in choice of independent variable, such as number and density of plants, whether the plants were floral or foliage only, the position of the plants in the building and whether they were near a window or not, and live or artificial.

Studies focused mainly on three areas (psychological well-being, physical health, and job satisfaction). The measured outcomes include psychological measurements (task performance, productivity, perceived stress, sick leave health and discomfort symptoms, mood, behavior, pain intensity, pain distress, anxiety, fatigue, and so on) and psychophysiological measurements (blood pressure, blood volume pulse, electromyography, and electroencephalography).

In the review, we discuss the heterogeneity on "effects of plants as reported" operation here in terms of exposure characteristics. Some findings recurred, notably reduced stress and enhanced performance and comfort when indoor plants were present, but in general the results were varied. The various results from the studies may be partly due to the heterogeneity in the use of the independent variables and different experimental design. Most studies found that indoor plants reduced nervousness or anxiety (Adachi et al. 2000; Chang and Chen 2005), and they have the potential to reduce stress (Bringslimark et al. 2007; Dijkstra et al. 2008; Evensen et al. 2015; Park and Mattson 2009). Some authors reported that indoor plants improved task performance and mood (Fjeld 2000; Han 2009; Shibata and Suzuki 2002, 2004), while another study showed that mood was not affected (Shibata and Suzuki 2001). The difference in task performance and mood may be due to the room arrangement of test, plants species, and arrangement. Putting plants in the enclosed space (underground floor) maintains above-ground ways of living and working and increases available space (Kim et al. 2018).

Another study found that indoor plants could promote human creativity and increase the comfort and attractiveness of the office environment, while at the same time decreasing worker productivity (Guéguen 2012; Raanaas et al. 2011). Some studies found beneficial effects were not gender specific (Shoemaker et al. 1992); however, others did not, with females having a stronger reaction to the affective source (Shibata and Suzuki 2004), and with males feeling more satisfied looking at indoor plants than did females (Dravigne et al. 2008). The study by Shoemaker et al. (1992) was conducted in the real space among employees, while it was conducted among undergraduate students in Shibata and Suzuki (2004). That may result in contradictory results.

The process of how the presence of indoor plants affects psychological performance is still unclear and warrants further study. The concept that plants play a role in mental health is well-established. Horticultural therapy is used in mental health treatment because of the therapeutic effects of gardening (Söderback et al. 2004). The question of whether contact with indoor plants could also contribute to healing from physical ailments, remains, and would need more evidence to support the idea. From a psychological perspective, indoor plant can be recommended as a low-cost and low-risk addition to workplaces, schools, and patient areas to improve outcomes for employees, students, and patients, as well as satisfaction with their working and living environments.

Purification

High concentrations of volatile organic chemicals (VOCs) and other chemical pollutants resulting from new furniture, home decoration, and household products are found indoors. These chemicals are known to cause irritation, allergic asthma, neurasthenia, and other respiratory problems (Deng et al. 2015; Tang et al. 2009). Some indoor VOCs are toxic and some, like formaldehyde and benzene, which at low concentrations can cause skin irritation and a dry throat, and at high concentrations have been shown to be carcinogenic. Evidence showed that the indoor was the first-line property of statistically significant higher level pollution than outdoor (Delgado-Saborit et al. 2009). Since people spent most of their time indoors, poor IAQ increases their risk of exposure to pollutants (Bernstein et al. 2008). Phytoremediation is a cost effective alternative technology for cleaning indoor air. A 35% lower concentration of VOCs was found in a classroom with plants compared to the same classroom without plants (Fjeld 2000; Fjeld et al. 1998).

Table 2 summarizes the efficiency of different indoor plant species in removing pollutants. From Table 2, we see that most of the studies investigate the removal of formaldehyde, benzene, toluene, xylene, and other pollutions. Different parts of a plant have different removal potential, with the efficiency of pollutant removal being plant specific.

The removal efficiency is both plant specific and air pollutant dependent. Different authors have used different units for determining decontamination efficiency, also differed in different plant species, pollution, pollutant concentrations, exposure duration, chamber sizes, and level of light; hence, it is not entirely reliable to compare results from different studies. Using plants to accumulate and metabolize formaldehyde is unlikely to be of value for indoor air purification due to the low uptake rate, while the cleavage of formaldehyde was typical for microbial degradation of compounds containing methyl or methoxyl groups (Orita et al. 2005). This meant that the root zone and rhizospheric microorganisms were the main parts of the plants involved in formaldehyde removal (Aydogan and Montoya 2011; Godish and Guindon 1989; Kim et al. 2008; Xu et al. 2010; Xu et al. 2011). The high activity of botanical and microbial enzymes contributed to the formaldehyde removal (Xu et al. 2011). Formaldehyde was enzymatically converted by specific dehydrogenase to formic acid and ultimately to CO_2 and H_2O, or alternatively assimilated into amino acids, sugars, and other bioproducts, according to the C1 metabolic pathway (Giese et al. 1994). Although formaldehyde cannot be metabolized by leaves, there is evidence that formaldehyde can be removed by adsorption of plant shoots (Dingle et al. 2000; Giese et al. 1994; Kim et al. 2010; Xu et al. 2011; Zhou et al. 2011). Environmental factors also play an important role in the efficiency of pollutant removal by indoor plants. It has been shown that 21 °C was the proper temperature for maximum formaldehyde removal of potted plants (pothos) (Sawada and Oyabu 2008) and was influenced by the presence or absence of light (Kil et al. 2008). That is controlling the proper light indoor and plants could effectively remove formaldehyde under indoors. Park and Ikeda (2006) indicated that indoor plants were more suitable for removing indoor-produced compounds in a new home rather than for a house that had been used for more than 3 years, maybe there was less pollution in new home than in old houses.

The deposition/accumulation of benzene appeared to be dependent on plant species and plant part. For example, Collins et al. (2000) found that the uptake of benzene in blackberry and apple leaves was greater than that of cucumber leaves. Leaves of various indoor plants were the primary plant parts for removing benzene (Cornejo et al. 1999; Liu et al. 2007; Mosaddegh et al. 2014; Yang et al. 2009a). It was assumed that enzymes were performing the first step in the oxidative transformation of benzene in plant leaves containing copper as the prosthetic group (Ugrekhelidze et al. 1997). Stomata and the wax cuticles of plants are also important areas for benzene uptake (Treesubsuntorn and Thiravetyan 2012). Therefore, it was the day stomata opening and night closing involving the pollution removal.

Some results suggested that benzene removal by hydrocultured plants was slower than for traditional potting

Table 2 Summary of the efficiency and species of indoor plants about removing pollutions

Removing pollution	References (authors, year)	Indoor plants	Removing rate	Parts of plant
Formaldehyde	Aydogan and Montoya (2011)	*Hedera helix*; *Chrysanthemum morifolium*; *Dieffenbachia compacta*; *Epipremnum aureum*	81–96% in 24 h	Roots
	Dingle et al. (2000)	*Chlorophutum comosum*; *ficus* sp.; *Sspiridra elatior*; *Dieffenbachia amoena*; *Epipremum aremum*	11%	Unknown
	Giese et al. (1994)	*Chlorophytum comosum* L.	88% in 24 h	Shoots
	Godish and Guindon (1989)	*Clorophytum elatum var. vittatium*	29–50%	Roots
	Kim et al. (2008)	*Fatsia japonica*; *Ficus benjamina* L.	80% in 5 h	Roots
	Kim et al. (2010)	*Osmunda japonica*; *Selaginella tamariscina*; *Davallia mariesii*; *Psidium guajava*; *Rhapis excels*; *Zamia pumila*; *Chlorophytum bichetii*; *Dieffenbachia*'Marianne'; *Tillandsia cyanea*; *Anthurium andraeanum*; *Nandina domestica*; *Lavandula* spp., *Pelargonium* spp.; *Rosmarinus officinalis*	90% in 5 h	Leaves
	Sawada and Oyabu (2008)	*Golden pothoses*	60–85 v h^{-1} m^{-3}	Unknown
	Teiri et al. (2018)	*Chamaedorea elegans*	6.5–90%	Leaves
	Wolverton and Mcdonald (1984)	*Chlorophytum elatum var. vittatum* (spider plant)	29–50%	leaf and shoot
	Xu et al. (2010)	*Chlorophytum comosum* L.	60% (8 g m^{-3} h^{-1})	Roots
	Xu et al. (2011)	*Spider plant*; *Aloe*; *Golden pothos*	90–95% (1.5–6 μg h^{-1} g^{-1})	Leaves
	Zhou et al. (2011)	*Scindapsus aureus*, *Asparagus setaceus*, *S. trifasciata* cv. *Hahnii*, *C. comosum*, *A. commutatum* cv. *White Rajah*, *A. commutatum* cv. *Red Narrow*, *A. commutatum* cv. *Treubii*, *S. pictus* cv. *Argyraeus*, *G. gracilis* and *P. sodiroi* cv. *Wendimbe*	95% in 7 days	Leaves
Benzene	Cornejo et al. (1999)	*Pelargonium domesticum*; *Ficus elastica*; *Chlorophytum comosum*; *Kalanchoe blossfeldiana*	85–95% in 24 h (0.6–8.5 μg g^{-1} 24 h^{-1})	Stomata
	Irga et al. (2013)	*Syngonium podophyllum*	95% in 7 days	Unknown
	Liu et al. (2007)	*Crassulaportulacea*; *2. Hydrangeamacrophylla*; *3* Cymbidium Golden Elf	60–80% (44–503 μg min^{-1} m^{-2})	Leaves
	Mosaddegh et al. (2014)	*O. microdasys*	95% in 48 h (1.18 mg m^{-2} d^{-1})	Leaves
	Parseh et al. (2018)	*Schefflera arboricola, Spathiphyllum wallisii*	93–94% in 75 min	Leaves
	Sriprapat et al. (2014)	*Zamioculcas zamiifolia*	95% in 72 h	Cuticles and stomata
	Treesubsuntorn and Thiravetyan (2012)	*Dracaena sanderiana*	66–70% in 24 h (59.67 nmol cm^{-2} in 24 h)	Wax and stomata
	Yang et al. (2009a)	*Hemigraphis alternata*; *Tradescantia pallida*; *Hedera helix*; *Asparagus densiflorus*; *Hoya carnosa*	2.61–5.54 mg h^{-1} m^{-3} m^{-2}	Leaves
	Zhang et al. (2011)	Transgenic plants of *Petunia hybrida* harboring the CYP2E1 gene	67% in 6 days (0.4 μg m^{-3} in 6 days)	Leaves
Toluene		*Hedera helix*	66.502 μg m^{-2} h^{-1}	Unknown

Table 2 (continued)

Removing pollution	References (authors, year)	Indoor plants	Removing rate	Parts of plant
	Cruz et al. (2014)			
	De Kempeneer et al. (2004)	*Azalea indica*	95% in 27 h	Phyllosphere
	Mosaddegh et al. (2014)	*D. deremensis*; *O. microdasys*	95% in 48 h (0.54 mg m^{-2} d^{-1})	Leaves
	Orwell et al. (2006)	*Spathiphyllum*; *Draceana*	90% in 5 days (2.2–549 mg m^{-3} d^{-1})	Leaves
	Orwell et al. (2006)	*Golden pothoses*	36–40 v h^{-1} m^{-3}	Unknown
	Sriprapat and Thiravetyan (2013)	*Zamioculcas zamiifolia*	95% in 72 h	Cuticles and stomata
	Sriprapat et al. (2014)	*S. trifasciata*, *Sansevieria hyacinthoides*	85%	Wax
	Yang et al. (2009a)	*Hemigraphis alternata*, *Tradescantia pallida*, *Hedera helix*, *Asparagus densifloru*, *Hoya carnosa*	5.81–9.63 mg m^{-3} m^{-2} h^{-1}	Leaves
	Tang et al. (2009)	Transgenic plants of *Petunia hybrida* harboring the CYP2E1 gene	67% in 6 d (1.0 μg·m^{-3} in 6 days)	Leaves
Xylene	Mosaddegh et al. (2014)	*D. deremensis*; *O. microdasys*	95% in 48 h (1.64 mg m^{-2} d^{-1})	Leaves
	Sawada and Oyabu (2008)	*Golden pothoses*	38–40 v h^{-1} m^{-3}	Unknown
	Sriprapat et al. (2014)	*Zamioculcas zamiifolia*	95% in 72 h (0.86 mmol m^{-2})	Leaves
Ethylbenzene	Mosaddegh et al. (2014)	*D. deremensis*; *O. microdasys*	95% in 48 h (1.35 mg m^{-2} d^{-1})	Leaves
	Sriprapat and Thiravetyan (2013)	*Zamioculcas zamiifolia*	95% in 72 h	Cuticles and stomata
	Sriprapat et al. (2014)	*S. trifasciata*, *Sansevieria hyacinthoides*	90%	Wax
m-xylene	Orwell et al. (2006)	*Spathiphyllum*; *Draceana*	90% in 5 days (2.3–336 mg m^{-3} d^{-1})	Leaves
Total volatile organic compound (TVOC)	Orwell et al. (2006)	*S.* '*Sweet Chico*' and *D.* '*Janet Craig*'	75% in 24 h	Potted-plant micro-cosm
	Smith and Pitt (2011)	*Ficus Alii*; *Dracaena Compacta*; *Philodendron Scanden*; *Philodendron Scanden*; *Dracaena Gold Coast; Calathea Triostar*	20% in 6 months	Unknown
Carbon dioxide (CO_2)	Irga et al. (2013)	*Syngonium podophyllum*	Up to 60% in 40 min	Unknown
	Oh et al. (2011)	*Spathiphyllum*; *Ficus benjamina*; *Chrysalidocarpus lutescens*	Unknown	Unknown
	Smith and Pitt (2011)	*Ficus Alii*; *Dracaena Compacta*; *Philodendron Scanden*; *Philodendron Scanden*; *Dracaena Gold Coast*; *Calathea Triostar*	Up to 50% in 6 months	Unknown
Carbon monoxide (CO)	Smith and Pitt (2011)	*Ficus Alii*; *Dracaena Compacta*; *Philodendron Scanden; Philodendron Scanden; Dracaena Gold Coast; Calathea Triostar*	Up to 90% in 6 months	Unknown
Octane	Yang et al. (2009a)	*Hemigraphis alternata*; *Hedera helix*; *Ficus benjamina*; *Hoya carnosa*; *Ficus benjamina*	3.76–5.58 mg m^{-3} m^{-2} h^{-1}	Leaves
Terpene	Yang et al. (2009a)	*Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densifloru,Ficus benjamina*, *Ficus benjamina*, *Tradescantia pallida*	8.48–12.21 mg m^{-3} m^{-2} h^{-1}	Leaves
		Chlorophytum comosum; *Ficus elastica*	9.8% h^{-1}	Leaves

Table 2 (continued)

Removing pollution	References (authors, year)	Indoor plants	Removing rate	Parts of plant
Trichloroethylene (TCE)	Cornejo et al. (1999)			
	Yang et al. (2009a)	*Hemigraphis alternata*, *Hedera helix*, *Tradescantia pallida*, *Asparagus densiflorus*, *Hoya carnosa*	5.79–11.8 mg m^{-3} m^{-2} h^{-1}	Leaves
Ozone (O_3)	Papinchak et al. (2009)	*Sansevieria trifasciata*; *Chlorophytum comosum*; *Epipremnum aureum*	95% in 2 h	Unknown
Aldehydes	Tani and Hewitt (2009)	*Spathiphyllum clevelandii*	65–80% (7.7–13.2 mmol m^{-2} s^{-1})	Leaves
Ketones	Tani and Hewitt (2009)	*Spathiphyllum clevelandii*; *Epipremnum aureum*	50–65% (2.4–8.9 mmol m^{-2} s^{-1})	Leaves

mix plants (Irga et al. 2013), as soil microorganisms played an important role in pollutant degradation. The transgenic plants, *Petunia hybrida* with high CYP2E1 gene expression, demonstrated a significant increase in absorption capacity of environmental benzene and toluene, and had obvious improved resistance to formaldehyde when compared to the wild plant (Zhang et al. 2011).

Indoor plants can remove toluene from the air via their leaves (Orwell et al. 2006; Yang et al. 2009a). The phyllosphere of *Azalea indica* with a toluene-degrading enrichment culture of *Pseudomonas putida* TVA8 has shown great promise for removing toluene from air (De Kempeneer et al. 2004). Studies to remove xylene (Mosaddegh et al. 2014; Orwell et al. 2006; Sawada and Oyabu 2008; Sriprapat et al. 2014), ethylbenzene (Mosaddegh et al. 2014), octane (Yang et al. 2009a), terpene (Yang et al. 2009a), and trichloroethylene (Cornejo et al. 1999; Yang et al. 2009a) from the air using indoor plants have been done. Other air pollutants such as ozone (Papinchak et al. 2009), CO (Smith and Pitt 2011), and CO_2 (Irga et al. 2013; Oh et al. 2011; Smith and Pitt 2011) have been shown to be removed by indoor plants. Tani and Hewitt (2009) found C3–C6 aldehydes and C4–C6 ketones could be taken up by the plant leaves and suggested that VOCs were metabolized in the leaf and/or translocated through the petiole. Most indoor plants can also reduce other materials, such as PM_{10} (Gawrońska and Bakera 2015; Lohr and Pearson-Mims 1996) and offensive odors (Oyabu et al. 2003), although the result differs according to the physiological mechanisms of the plants. The indoor PM_{10} can be removed by neutralizing the indoor particle pollutant by plant-derived anions.

The most effective in reducing indoor air pollutant indoor plants were summarized in article by Franchini and Mannucci (2018), and they are *Chamaedorea seifritzii*, *Aglaonema modestum*, *Hedera helix*, *Gerbera jamesonii*, *Dracaena Deremensis* "*Janet Craig*", *Dracaena marginata*, *Dracaena massangeana*, *Sansevieria laurentii*, *Chrysantheium morifolium*, *Spathiphyllum* "*Mauna Loa*", *Ficus benjamina* and *Dracaena* "*Warneckii*". However, there is no designation of what contaminant or condition is.

Indoor plants are therefore useful for both decorating an area and improving the indoor air quality (IAQ). Care must be taken in selecting indoor plants for purification or decoration, as research has suggested that certain indoor ornamental plants release VOCs (Yang et al. 2009b). Species can be classified according to their purification capacity and the best ones used for phytoremediation indoor where air pollution is a concern. Plant combination with particular microorganism substance, transgenic plants, or plants embedding gene of encoding degradation enzyme would be explored for phytoremediation of certain environmental factors and for the botanical biofiltration of polluted air, and would greatly improve the efficiency and time of purification.

Conclusion and perspective

This review looked at the benefits provided by indoor plants resulting from: photosynthesis; transpiration; psychological effects; and air purification. To our knowledge, this is the first comprehensive summary of research into the basic functions of indoor plants and their relation with humans. The numerous studies referenced here, look at the function of indoor plants from around the world, and demonstrate how indoor plants affect people psychologically, and how they can be used for indoor air remediation. Indoor plants can greatly improve IAQ by removing many indoor pollutants. They are also able to release more O_2 and NAIs under certain conditions, as well as adjust the temperature and humidity to some extent, both functions being beneficial to humans. Indoor plants can be considered to be a self-adaptive, self-adjusting, flexible, transplantable, low-cost, sustainable, and esthetic biofiltration and bioremediation system, and so contribute to human health and comfort.

The perspective presented in this review, in spite of being speculative to some extent, raises some interesting questions that should be addressed in future research. Apart from those, plants are ideal adaptive structures with smart sensing capability gained from studying electrical, mechanical, and hydraulic progresses, which applied in environmental monitoring, agriculture, and area monitoring (Afsharinejad et al. 2016; Volkov and Ranatunga 2006). Plants could be cognitive and intelligent. Based on the amazing sensing capability of plants, an intelligent system was designed to enable non-emotional interaction between humans and indoor plants. It was reported that plants could emit and receive sound and so communicate with humans (Monica 2013), but the underlying mechanism of how and why they issue sound, remains a mystery. Further research into the sensing capability of indoor plants could help to explain these phenomena, and an application of the developed green system for the acoustic treatment has been reported by D'Alessandro et al. (2015).

Greenhouse plants provide food for humans and great progress has been made in other closed environments to determine proper climatic conditions for crop culture in space (Ferl et al. 2002; Kitaya et al. 2000). This research looks into the possibility of using indoor plants to supplement crew diets in long space mission. These plants could also be used to convert local CO_2 and H_2O to O_2 in addition to providing food.

Photosynthesis provided a blueprint for the generation of solar energy, an energy source not based on fossil fuels (Alharbi and Kais 2015; Raji et al. 2015). Solar energy is one of the few alternative energy sources that could be scaled up to meet our future needs. Artificial photosynthesis helps us to learn from photosynthesis to reproduce the same principles using solar energy to create H_2 from water. This will have a remarkably positive impact on energy in the future (Alstrum-Acevedo et al. 2005). Although attempts to find an effective chromophore catalyst for use in artificial photosynthesis was an issue, solar fuel production was achieved in a laboratory, and more research is needed to identify the most promising artificial photosynthesis systems and to realize their potential (Gust et al. 2009). Artificial photosynthesis systems are able to transform H_2O to H_2 fuel (Liu et al. 2016). If these systems can be made to convert CO_2 to methanol or some other C source, they could be used to reduce CO_2 to control global warming.

The first artificial leaf for power generation was developed by (Nocera 2012), providing an inexpensive and highly distributed solar-to-fuel system (Bensaid et al. 2012; Michl 2011). This development provides an opportunity to develop non-biomimetic photosynthesis, and investigating progress in "artificial plant" systems in the future. These systems include the operational mechanisms of mimicking functions of indoor plants. Only sunlight, CO_2, H_2O, and artificial plant, will be needed to produce automotive fuels, polymers, butanol, and macromolecular material in the future. Figure 2 shows some speculative development of photosynthesis in the future.

Some general guidelines for choosing indoor plants good for human health and comfort include the following: Firstly, the indoor plants should have tolerance to pollutant, not only removing some pollutant, but also not releasing pollutants. Secondly, although there is a certain psychological effect of indoor plants on patients in the hospital, potted plants will bring some pathogenic bacteria, and it is recommended to use hydroponics plants in the hospital. Not in the bedroom is recommended at night as it could release CO_2 by respiration. Thirdly, floral plants are recommended for postoperative recovery in hospital, while foliage plants for workplaces, and large landscape facilities for energy-efficient buildings. Finally, spider plants are usually used to remove formaldehyde of new renovated house, and multiple varieties combine to remove multiple contaminants. There are challenges to make meaningful contributions to human health and comfort of indoor plants, like botanic biofilter, artificial photosynthesis, and space food. Facing many adventures and challenges,

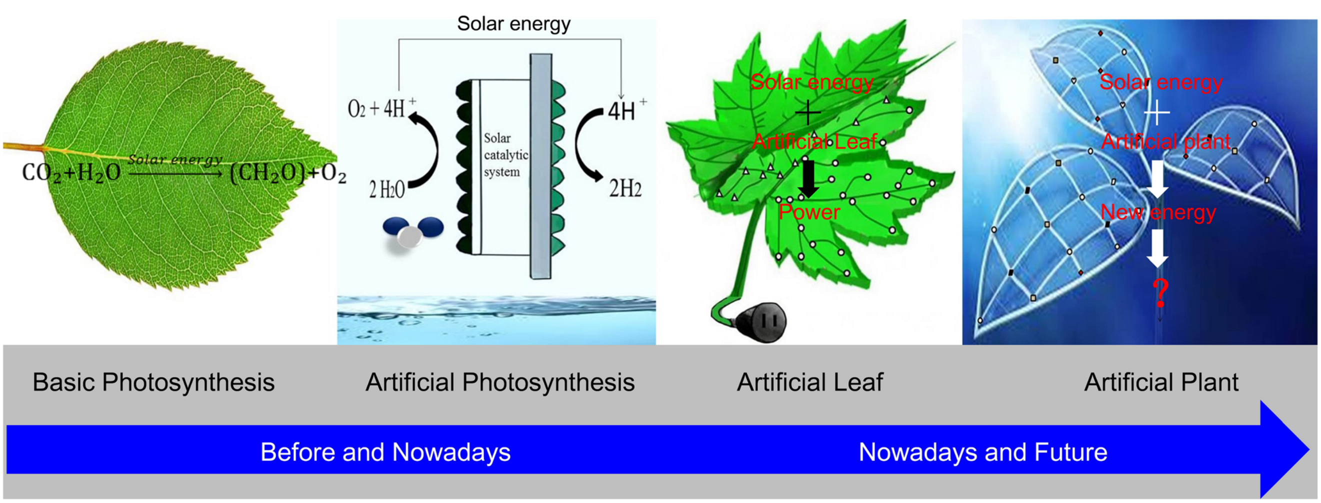

Fig. 2 Speculating the development and application of photosynthesis in the future

finding the key process or participating microorganisms or mainly gene of plants and degrading enzyme for pollution removing is of significance for the future studies.

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