The Impact of Plants on Indoor Air Quality, Energy Use, and Psychological Status of Occupants

by

Shaimaa Fouad Mohamed Abdelhamid Seyam

A thesis submitted in conformity with the requirements
for the degree of Master Science
Department of Civil Engineering
University of Toronto

The Impact of Indoor Plants on Indoor Air Quality, Energy Use, and Psychological status of Occupants

Shaimaa Fouad Mohamed Abdelhamid Seyam

Degree of Master Science

Department of Civil Engineering
University of Toronto

2017

Abstract

Plants may have several impacts, which can be categorized into indoor air quality, energy use, and psychological effects. This thesis presented a comprehensive review of the impact of indoor plants in these categories. Indoor plants can emit a negligible amount of VOCs and microorganisms to the indoors but also have limited ability to remove pollutants. In addition, greenery systems are exterior to the building enclosure, resulting in a reduction of external surface temperature and heat transfer, particularly in certain climates. Interaction with indoor plants can also deliver measurable psychological benefits to people despite the confounding variables and other experimental design issues. In conclusion, indoor plants have limited effect on indoor air quality, external plants have a possible impact on saving energy, and indoor plants can influence psychological status when placed on the level of vision. Plants cannot be treated as a system, and other alternatives can provide promising solutions.

This thesis is dedicated to my God and His Messenger Mohamed (Peace be upon him (PBUH)) who always encourage the believers to gain knowledge and never stop learning. Thank you Allah!

Acknowledgments

How I thank people before I thank my Lord who created the people who help me and created everything in the universe. I am so grateful to Allah who let the destiny chose me and my husband to travel to Canada and pursue our graduate studies. The first verse that revealed to Prophet Mohamed (PBUH) was Read-Read-Read. The Muslim Ummah are suffering from illiteracy and tyranny, and it is my duty to travel far away from my family and my country to gain knowledge to assist the Muslim Ummah. My hope is to benefit the Muslim Ummah and other interested nations with my master thesis.

I am so grateful to Allah who let Prof. Jeffrey Siegel to be my supervisor. He is a brilliant researcher and a professional writer. He also was and still patient, supportive, and advisor through my challenges in research and writing during my journey of master thesis. I will be not grateful if I don't mention the staff of the University of Toronto during their collaboration in my administrative work. Also, the instructors and professors of my courses are thankful for helping me in comprehending the course materials. In addition, the colleagues in my research team are thankful for their support and their pleasurable time.

A great thanking to my supportive and beloved husband Amro Ibrahim by providing a good studying environment and taking care of our children. In addition, recognizes to my parents who prayed for me during my challenges.

Thanks to All!

Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1 Motivation and Objectives

This thesis focuses on the impact of indoor plants on the three categories: indoor air quality including pollutant removal and emission, energy use, and psychological effects on occupants. The thesis covers recent previous investigations to measure the impact of indoor plants in each of these areas.

1.1 Motivation

People, in general, spend around 90% of their time indoors (Leech et al., 1996; Klepeis et al., 2001). This large amount of time spent indoors is often associated with several adverse consequences. Such consequences are divided into three categories as follows: first regarding to indoor air quality, occupants are exposed to a number of potentially harmful pollutants from internal sources, including smoking, cooking (Robinson et al., 2006), vacuuming (Dales et al., 2008), building materials, furniture, and office equipment (Kagi et al., 2007), and external sources, including penetration of pollutants from outdoors. Exposure to these dangerous pollutants may cause adverse health effects and cause poor indoor air quality (Kampa and Castanas, 2008). Second regarding to enegy use, building occupants have a profound impact on its energy consumption. This impact is primarily governed by occupant comfort based on building operational parameters, such as the indoor air temperature, relative humidity, lighting levels, and required ventilation. Maintaining comfortable conditions requires a substantial amount of energy largely from the use of heating, ventilation, and air conditioning (HVAC) systems (Web Source: C2ES, 2013). Third regarding to psychological effects, a poor indoor environment may be associated with psychological impacts, including decreases in work productivity (Singh, 1996; Vuokko et al., 2015) and health issues, resulting in an increase in medical expenses (Seppanen and Fisk, 2006). Therefore, these categories are indoor air quality (IAQ), energy use and psychological effects. They have become prominent research areas to assure occupant health and building sustainability. Indoor plants may provide positive solutions and may have a positive influence on indoor air quality, energy use, and productivity and perception indoors.

1.2 Previous Literature Reviews

Indoor plants may provide positive solutions and have an effective influence on three distinctive categories: indoor air quality, energy use, and psychological study. Nineteen review papers have analyzed the impact of plants in the three categories central to this work. Five reviews in indoor air quality have discussed pollutant removal mechanisms (Soreanu et al., 2013), different biological treatments (Guieysse et al., 2008), biofiltration performance and research methodology (Girman et al., 2009), and the mixed findings of laboratory and field research (Tarran et al., 2007). Nine reviews in energy use have presented the definitions, classifications and designs, and thermal performance benefits associated with plants (Castleton et al., 2010; Jaafar et al., 2012; Perini et al., 2013; Hunter et al., 2014; Pérez et al., 2014; Safikhani et al., 2014; Wang et al., 2014; Manso and Castro-Gomes, 2015; Raji et al., 2015). Finally, five reviews have considered some psychological benefits of the physical features of built environments including the external internal exposur to nature in health care facilities (Salonen et al., 2013), labour productivity (Bakker and van der Voordt, 2010), therapeutic activities on elderly (Detweiler et al., 2012), and the experimental design of previous psychological research (Bringslimark et al., 2009). These studies have reviewed the benefits of plants in a particular context. In the following sections, I will present a summary of each review paper about their common research interest point and the extent of the impact of indoor plants on each by introducing a conclusion at the end. Also, I will introduce the purpose of my review.

1.2.1 Indoor Plants and Indoor Air Quality

Five review papers, which are listed in Table 1.1, report the effect of indoor plants on the indoor air quality. Table 1.1 organizes the reviews based on their research interest such as plants species, biofiltration configuration (e.g., biofilters, biotrickling filters, etc.), contaminant used, and studied parameters.

The five reviews have covered plentiful articles as shown in Table 1.1. More than 100 plant species were investigated (Cruz et al., 2014) with respect to their pollutant removal. Guieysse et al. (2008) and Soreanu et al. (2013) defined biofiltration systems as systems which use biological processes to remove contaminants from the air. These processes can be performed by microorganisms, plants and their rhizosphere microorganisms. These systems include biofilters, biotrickling filters, bioscrubbers, and botanical biotrickling filters. They are reactors in which the contaminated air is introduced passing into a moist porous media, and the water is continuously distributed on the media and the air with the same or counter direction of the air flow. The treatment processes are different for each depending on the packing material of media and the additional bioreactors to the water flow. In biofilters, the packing material is a natural material supports microbial growth, and the clean water with or without nutrients is circulated through the media and no need for extra bioreactors. In biotrickling filters, the packing materials are inert materials (ceramics, resins, etc.), and the aqueous solution contains nutrients for microbial growth to biodegrade the contaminations in the media. In bioscrubbers, the aqueous solution is added to the media to wash the contamination from the air, and the washed liquid is transferred into a bioreactor to biodegrade the contaminations.

Table 1. 1: List of review papers analyzing the relationship between plants and indoor air quality

Reference	Included articles	Plant species	Biofiltration systems	Contaminants		Parameters		
				VOCs*	ICs*	RR*	η*	others
Tarran et al. (2007)	36			●	●	●		●[a]
Guieysse et al. (2008)	118		●	●			●	●[b]
Girman et al. (2009)	6			●				●[c]
Soreanu et al. (2013)	102		●	●	●	●	●	●[d]
Cruz et al. (2014)	136	●		●		●	●	●[e]

* VOCs=Volatile organic compounds, ICs=inorganic gaseous compounds, RR=Removal rate, and η=Removal efficiency

[a] Experimental studies and procedure. Studies conducted in real locations

[b] Biological treatment, Humidification, hazards, and some positive effects

[c] Experimental time, locations, and volume of test chambers.

[d] Removal pathways and plant physiology

[e] Removal pathway, other effects such as light, temperature, growing media, VOC low concentration and identity

Plants can also be used as biofiltration systems which contain two types (Guieysse et al., 2008; Soreanu et al., 2013). The first system consists of potted plants into a sealed chamber, and the polluted air is introduced into the chamber and settled for a period of time for biodegradation though plant leaves and soil. The second system is a botanical biotrickling filter, which consists of a biotrickling filters equipped with hydroponic plants and a packing materials of roots support without and with soil, and the aqueous solution is continuously circulated to the soil with microorganisms and nutrient solution. This system. The contaminated air is introduced to the roots support or soil (the plant leaves may not be included) and washed by the aqueous solution and biodegraded by roots, soils, and the microorganism in the soil and roots.

All reviews have studied the varieties of VOCs with plants as shown in Table 1.1. The most common VOCs tested with plants are formaldehyde (e.g., Kim et al., 2010), benzene, toluene, ethylene, and xylene (e.g., Liu et al., 2007; Mosaddegh et al., 2014). Also, two reviews (Tarran et al., 2007; Soreanu et al., 2013) have combined the inorganic gaseous compounds (ICs) (i.e., CO_2, SO_2, CO, and NO_2) in their studies. In addtion, the roles of plant biology have recently encouraged Soreanu et al. (2013) and Cruz et al. (2014) to present the processes of pollutant removal, as listed in Table 1.1. They have elucidated the removal mechanisms, pathways of contaminants, and gas biodegradation (ICs and VOCs). Plants have two main parts: above the ground and below the ground. Above the ground where the leaves play an important role by absorbing organic and inorganic gas, while roots, microorganisms, and growing media have important functions in biodegradation and removal below the ground.

In order to evaluate the performance of indoor plants as biofilters, most reviews have concerned removal rate and removal efficiency of pollutants as common parameters. The contaminant removal rate is defined as the rate of removing a contaminant from an environmental space, and the removal efficiency is the ratio of the amount of contaminant removed compared to the initial contaminant amount/concentration. These parameters can be influenced by plants species, growing media of the plant, environmental factors such as light intensity and temperature, and the concentration and identity of the pollutants (Cruz et al., 2014). Other parameters include other benefits of indoor plants, such as aesthetic purposes, noise abatement, and human perception (Guieysse et al., 2008; Soreanu et al., 2013).

Overall, the botanical biofilters can purify the contaminated air since potted plants can have high removal efficiencies reaching to 90% according to plant species and pollutant identity (VOCs or ICs) (Tarran et al., 2007; Girman et al., 2009; Cruz et al., 2014). These removal efficiencies were proven in laboratory studies captured in the reviews. However, the biofiltration systems operate at low volumetric treatment flow rate to maintain the removal efficiency (Guieysse et a., 2008). In addition, the findings in real-life settings did not support the findings in laboratory studies and showed other contributions to removal including ventilation systems (Girman et al., 2009; Cruz et al., 2014).

1.2.2 Plants and Energy Use

Greenery systems refer to constructing external plants on the building enclosure. These systems are the main focus instead of indoor plants because they have a negligible effect on energy consumption. There are nine review articles, which are organized in Table 1.2, and the common topics mentioned in these reviews are types of greenery systems, classifications, system design, methodology, thermal performance, energy savings, and the climate change, which are discussed below.

Table 1.2: Previous literature reviews related to plants and energy savings

References	Greenery systems				Classifications	System Design	Methodology	Thermal performance	Energy saving or heat flux	Climate change
	GF	LW	GR	others						
Manso and Castro-Gomes (2015)	●	●			●	●		●		
Raji et al. (2015)	●	●		●*				●	●	
Hunter et al. (2014)	●					●		●	●	●
Pérez et al. (2014)		●	●		●		●	●	●	●
Safikhani et al. (2014)	●	●			●			●	●	
Wang et al. (2014)		●	●	●**			●	●	●	
Perini et al. (2013)	●	●			●				●	●
Jaafar et al. (2012)	●	●			●			●		
Castleton et al. (2010)			●						●	

* Green balconies, indoor sky gardens

**Adjoining vegetation

As shown in Table 1.2, the classifications of greenery systems are presented in four reviews (Jaafar et al., 2012; Perini et al., 2013; Pérez et al., 2014; Safikhani et al., 2014; Manso and Castro-Gomes, 2015). Greenery system is a descriptive term of using plants on the building envelope. The classification of greenery systems depends on the location of plants and growing media (Pérez et al., 2014; Manso and Castro-Gomes, 2015). When the growing media is the ground, the system is called green façades, which have two main branches: direct façades including traditional or double skin façades, and indirect façades including continuous guides or modular trellis. When the growing media is embedded in the building walls, the system is called living walls or green walls, which also have two main branches: continuous green walls by using continuous screen or geotextile felt, and modular green walls by using trays, vessels, or planters. Lastly, when the growing media is on the roof of a building, this system is called green roofs. The main types of greenery systems are green façades, living walls, and green roofs, which are common among the nine reviews. Less commonly investigated are green balconies, indoor sky gardens (Raji et al., 2015), and adjoining vegetation (Wang et al., 2014).

In addition, vegetation system design (Hunter et al., 2014) and system requirements (Manso and Castro-Gomes, 2015) are important to understand how greenery systems work and affect buildings based on extra layers that added to the building envelope, as shown in Table 1.2. These systems requirements are supporting elements, substrate, drainage, irrigation, and planting. Hunter et al. (2014) discussed the requirements for green façades, and Manso and Castro-Gomes (2015) discussed the requirements for living walls and green façades. The majority of these reviews have focused on the microclimate of building envelope. This envelope contains uninsulated building structure, air cavity, vegetation cladding (plants and/or soil), and metal frame support, such as stainless steel or aluminum.

Moreover, the methodology has been categorized into experimental studies, observational studies, and numerical studies (Pérez et al., 2014; Wang et al., 2014), as shown in Table 1.2. First, the experimental studies can consist of two flat blocks: with vegetation and a bare block as a control block under the same environmental conditions. Internal and external surface temperatures and relative humidity are the most and main parameters in these studies, and the majority of results are surface temperature differences and heat flux through walls or roofs. Second, the observational studies are applied to an office or a room in a real building, by choosing a whole or a portion of a wall with vegetation for living wall system or a roof with vegetation for the green roof system. The results of vegetated envelopes are compared to results of a bare wall or a bare roof. The studied parameters are internal and external surfaces temperatures, vegetation temperatures, relative humidity, and heat reduction. The selected rooms in these studies are vacant and made of concrete or brick. Third, numerical studies have carried out by using a computational simulation or mathematical modeling. The most studied parameters are the thermal behavior of the greenery systems, the effects of irradiance and wind reductions, the effect of the orientations, the effect of foliage coverage, and the energy consumption of buildings.

The review papers have also studied the thermal performance of greenery systems, as illustrated in Table 1.2, in seven articles (Manso and Castro-Gomes, 2015; Raji et al., 2015; Hunter et al., 2014; Pérez et al., 2014; Safikhani et al., 2014; Wang et al., 2014; Jaafar et al., 2012). Thermal performance can be defined as the temperature difference between building envelope layers, and sometimes relative humidity. The comparison between building envelopes with and without vegetation are necessary to measure the difference in heat flux through the building envelopes under the same environmental conditions. Consequently, vegetation has a significant influence on the building envelope by decreasing the surfaces temperature of the envelope layers, which yields to lower power consumption. This decrease is a result of absorbing solar radiation by plant leaves and blocking it from passing through the building envelope. Also, the evapotranspiration of leaves produces a relative cold and moist air, which lower the temperature of the surroundings. The reductions can vary according to seasons and climates.

Moreover, energy savings were studied in several reviews, and only one literature has investigated the effect of greenery systems on the HVAC systems (Raji et al., 2015). The energy saving can be related to the saving in electrical power consumption or the reduction of heat transfer through the building walls and roofs, but they are described separately in the current thesis. Vegetation provides the cooling effect on the building envelope and reduces the temperature of ambient air, which is used as cold air instead of using chillers to cool the air in air conditioning systems (Castleton et al., 2010). Raji et al. (2015) reviewed energy demand for each of vertical greenery systems, green roofs, and green balconies. The vegetation on the building envelope works as an external insulation, which may reduce energy demand. Living walls and green façades can reduce heat transfer through walls by 20% to 50% and green balconies more than 50%. However, green roofs have a different impact by adding more weight and more moisture content than buildings without green roofs. They are effective in the summer season. However, they may consume more energy due to more heating load in the winter season because of the excessive moisture content.

Finally, previous studies were also classified according to the climates and locations in three reviews (Perini et al., 2013; Pérez et al., 2014; Hunter et al., 2014). The world weather mapping known as world map Koppen-Geiger climate classification (Pérez et al., 2014) was a useful tool to distribute the locations of studied greenery systems over a colour-coded, world map according to climate. The results showed that the majority of studies are in Western Europe and South Eastern Asia. For plant species, the most common used for green façades are evergreen or deciduous climbing plants, and for living walls are evergreen herbaceous or shrubs species.

These reviews haves explored the benefits of greenery systems. The plants can insulate the buildings from solar radiation, reduce surface temperatures of building envelopes, abate noise, and produce aesthetic benefits. Previous studies have conducted laboratory investigation on greenery systems in different kinds (experimental, observational, and simulation studies), which have shown significant impact of greenery systems on reduction of heat transfer. However, there was limited analysis on field investigations, which needed to be studied.

1.2.3 Plants in Psychological Research

There are several review articles from different perspectives dealing with human physiology and psychology associated with the indoor plants. This section focuses on five recent reviews and how the indoor plants were introduced to improve human health and psychological status. For example, Detweiler et al. (2012) reviewed the effect of gardening activities in horticulture therapy especially with elderly people that have medical and mental health problem. The gardening activities included indoor gardening, therapeutic gardening, and viewing to external gardens. The findings showed that horticultural therapy may reduce pain, improve attention, decrease stress, modulate agitation, and lower medications which would possibly reduce the medical costs. However, there are few controlled clinical trials that demonstrate the positive and negative effects of passive or active rehabilitation of the elderly in the garden settings.

In addition, Salonen et al. (2013) reviewed the main factors to enhance the indoor environment in the healthcare design and operation facilities. The indoor environment can be expressed as visual interaction including nature views, thermal environment, ventilation and air conditioning systems, acoustic environment, and others. In healthcare settings, visual experiences of patients to plants, such as gardens, provide beneficial effects. The view of nature has been associated with reduced levels of outcomes: stress, anxiety, delirium, depression, pain, which results in the need for strong medications. In addition, the impact of the view of nature on the staff in the healthcare can reduce stress, improve performance and productivity, increase job satisfaction, and improve concentration. Accordingly, the healthcare institutions have provided gardens for both patients and their families, which affect the physiological restoration for a short time, improve mood, and increase satisfaction. Furthermore, exposure to indoor plants may increase pain tolerance, improve pain control among patients and improve staff wellbeing.

Moreover, a new way of human interaction with nature is represented as the biophilic design, which encourages the use of natural systems and processes incorporated into the built environment. Gillis and Gatersleben (2015) reviewed the psychological benefits associated with the restorative environment. The experiences of biophilic design include direct experience of nature (e.g., light, air, water, and plants), indirect experience (e.g., images of nature, natural materials, natural colors, and natural geometries), and experience of space and place (e.g., the integration of part of whole and transitional spaces). Their purpose is to examine the literature of biophilic design on perceptions and attributes of occupants. The presence of nature provided benefits to human wellbeing from the restorative perspective. Nevertheless, there is no sufficient evidence about the restorative and psychological effect of the process and material use.

The research methodology including the experimental variables and procedures and the validity of such research was also included. For example, Bakker and van der Voordt (2010) reviewed the influence of indoor plants on labor productivity to examine some hypotheses and the reliability and validity of previous research in this concern. Seventeen research articles were analyzed according to similarities and dissimilarities with regards the following: plants and their characteristics and appearance, subjects and their distribution, surroundings, and research methods and variables. Diversity was major common in experimental parameter selection, settings, samples, exposure durations, and measures, and the effects of plants. The lack of information about plants and surroundings and precise description of research design may affect the validity of investigation. However, indoor plants may provide a positive impact of on labour productivity.

Another example about the research methodology and the impact of plants on occupants, Bringslimark et al. (2009) critically reviewed the experimental literature on the psychological benefits of indoor plants. They discussed the construct validity, internal validity, statistical conclusion validity, and external validity of 21 review articles. For the construct validity, many studies were interested in the visual experiences of plants, their location inside the rooms in the level of vision, and exposure time. The dependent measures were not specific and were than one outcome. For the internal validity, extraneous factors during the experiments were less controlled, which may cause conflicting results. Therefore, it is required to repeat the experiments several times to assure the internal validity. For the statistical conclusion validity, there is a small effect of plants on some outcomes because of insufficient statistical power and the type I error, so it is recommended to conduct on a large sample size to reduce such errors. Finally, there are potential limits to generalizing the findings, which affect external validity.

In general, the indoor plants can provide psychological benefits on occupants and can be used in therapies to improve human health. More controlled clinical and experimental studies are needed with large sample sizes to ensure the research validity and empower the notion of using plants in residential and commercial buildings.

1.3 Thesis objectives and organization

Based on the previous information, the indoor plants have been investigated separately in each category, which showed promising results. However, few studies were conducted in real settings, and showed the indoor plants have limited effects. I found that there is a strong need to make a review article in order to investigate whether the indoor plants have impact on each category: indoor air quality, energy use, and psychological status for many reasons as the following:

1. The three categories are studied explicitly.
2. The previous reviews have focused on experimental setups, system configurations, parameter selection, and mechanisms of applications.
3. Few reviews have captured field studies (real settings) and their results did not support the experimental studies (Girman et al., 2009; Bringslimark et al., 2009; Bakker and van der Voordt, 2010; Detweiler et al., 2012; Cruz et al., 2014).
4. The impact of plants was not evident in each category since there is a large discrepancy in field and laboratory studies.

Therefore, the current thesis investigates the effect of indoor plants on the three categories, by reviewing and analyzing previous studies in each and integrating their effect in different scenarios.

1.4 Thesis Objectives

The purpose of the current thesis is to provide a comprehensive analysis of the impact of indoor plants on the three categories of the indoor air quality, energy use, and psychological effect, and to assess the impact of plants in real life. I present my research questions as follows:

1. Do the indoor plants have an impact on indoor air quality?
2. Does the emission of indoor plants have an effect on indoor air quality and occupants?
3. Do the plants have an influence on the energy consumption of a building?
4. Do indoor plants have a significant influence on human perception and improve their psychological status?
5. What are the overall impact if the impacts are integrated into real sittings?

1.5 Thesis Organization

The current thesis addresses the above information in Chapter 2-4. Chapter 2 presents the research methodology and some of the governing equations. Chapter 3 reviews the impact of plants on each category: indoor air quality including removal and emission of pollutants, energy use, and psychological effects. Chapter 4 discusses the impact of plants in each category and addresses the limitations of the current thesis. Finally, Chapter 5 presents the final conclusions of the thesis.

Chapter 2 Methodology

This chapter covers the research methodology for selecting articles in each of the following categories: indoor air quality, energy use, and psychological effects. Also, this chapter presents the governing equations and assumptions to estimate the clean air delivery rate (CADR) value and the effectiveness based on a selected scenario.

2.1 Research Methodology

There are three primary fields about plants in this paper: indoor air quality, energy savings, and human perception. The central databases used in research for such themes are Web of Science (https://apps.webofknowledge.com) and Google Scholar (https://scholar.google.ca). The searching process through databases is quite similar for each field. Since we focused on indoors and the relationship between plants and occupants, the keywords for plants are: “indoor plants”, “indoor potted plants”, “plants”, “green plants”, “potted plants”, “ornamented plants”, “indoor gardening”, “vegetation”, “greenery”, “vertical greenery systems”, “green façades”, “living walls”, “green walls”, or “green roofs”. The first seven keywords combine the plants related to indoor air quality, emissions from plants, and human perception. The next seven keywords are related to energy savings. These keywords for indoor plants are used in correlation with the next other keywords to search for articles related to each field.

The other keywords for each category are used for searching as the following: for indoor air quality (IAQ) and emissions from plants, this category can be divided into two subcategories to facilitate searching through databases. For IAQ, the keywords used are: “indoor air quality or (IAQ)”, “volatile organic compound/s or (VOC/s)”, “formaldehyde”, “contaminants”, “indoor air pollution”, “removal efficiency”, “removal rate”, “clean air delivery rate or (CADR)”. Using these words yielded a total of 95 articles. I have found five review articles (described in the last chapter (Tarran et al., 2007; Guieysse et al., 2008; Girman et al., 2009; Soreanu et al., 2013; Cruz et al., 2014) and 55 research articles about 30 articles were studies in the previous reviews. For emissions from plants, I used: “emissions”, “source of emissions”, “emissions from plants”, “microbial”, “fungi”, “biogenetic volatile organic compounds or (BVOCs)”, or “biohazards”.

The collected articles were focused more on outdoors than that on indoors, and less than ten are related to emissions from indoor plants and related to indoor air quality. Same searching trend was used for energy saving: “energy saving”, “energy consumption”, “power consumption”, “heat flux”, “energy reduction”, or “heat reduction”. The results for this searching process was over 100 articles. After filtering the articles close to plants and energy saving, there are nine literature reviews (mentioned in Chapter 1, and they are (Castleton et al., 2010; Jaafar et al., 2012; Perini et al., 2013; Hunter et al., 2014; Pérez et al., 2014; Safikhani et al., 2014; Wang et al., 2014; Manso and Castro-Gomes, 2015; Raji et al., 2015) and 32 research articles. I focused on articles that published in the range from 2010 to 2016 since there are many review papers covered many research articles and capturing 10 articles from my list. Finally, I also used the following keywords for human perception: “human perception”, “human physiology”, “human psychology”, “mental relief”, “workplace environment”, “productivity”, “participant’s mood”, “mood”, or “concentration”. I have found five review papers (Bringslimark et al., 2009; Bakker and van der Voordt, 2010; Detweiler et al., 2012; Salonen et al. 2013; Gillis and Gatersleben, 2015) and 20 articles that are published from 2010 to 2016, and less than 10 articles are included in previous review papers.

This thesis focuses on research articles or reports that have conducted laboratory and field investigations in each category. In addition, any reviews related to the impact of indoor plants or greenery systems are helpful to increase my knowledge in the research area that I have limited knowledge such psychology and plant biology. This method will help in answering the research questions by a critical analyzing the investigation results and study the impact of indoor plants.

In the current thesis, I captured more than a hundred research articles including experimental investigations (95 articles) and field investigations (about 10 articles). All articles are organized in tables, presented in Chapter 3 and 4, based on input parameters and main findings which help to assess the impact of indoor plants. For studying the impact of indoor plants on indoor air quality, I used some equations in order to calculate the clean air delivery rate (CADR). Several reasons are included as follows: main studied parameters are removal rates and efficiencies, most of the captured articles (about 30 articles) are included in the five reviews, and another method is needed to evaluate the actual removal capacity of indoor plants and helps to understand the differences between laboratory and field studies. That presents in calculating the CADR, which was not calculated among the studies. This method is explained in the next section. For other categories, I analyzed the input parameters and the results based on the captured articles.

2.2 Clean Air delivery rate (CADR)

Two main parameters are removal rate and removal efficiency included in investigating the effect of indoor plants on the indoor air quality. They depend on the initial and final pollutant concentration. In this thesis, another parameter, clean air delivery rate (CADR), is presented to assess the ability of indoor plants to remove pollutants similar to air cleaning devices since it has been used since 1980s (ANSI/AHAM AC-1-2006)

The CADR is defined as the rate that indoor plants produce clean, purified air to a room or space, and its unit is cubic meter per hour (m^3/h). It is calculated based on the given data found in the selected articles, which include the type and identity of the VOCs, the removal rate, the removal efficiency, the plant species, the chamber volume, and the experimental time. Any articles that did not provide such data are excluded from the investigation. Moreover, a scenario is also presented to simulate a typical office with indoor plants as air cleaners, which is helpful to measure the effectiveness of plants in a real location.

Before introducing the CADR equations, the experimental setups should be included in all of selected articles, and the assumptions should be stated. Laboratory studies are the main selection and main type of articles that conducted experiments. The experimental setups have three parts: preparing of an air flow containing a constant concentration of a specific pollutant, a sealed test chamber, and an analysis system using a gas chromatograph equipped with an ionization detector. The contaminate of interest is injected with the inflow air to the chamber. A fan is placed in the middle of chamber to ensure the distribution of the mixture. The contaminated air stays inside the chamber for a period of time. The air sampling was collected after a certain period of time, and the final concentration was measured and recorded until no change in the outlet air sampling concentration.

In addition, several assumptions should be considered. Each article includes the following assumptions: the test chamber is well sealed and has well-mixed air inside it, the air density is constant because most of the physical experiments have done under a constant temperature in a range of 20 to 26 °C and no external air flow enters the sealed chamber, the outdoor concentration is neglected because the chamber is sealed and no ventilation and infiltration rates, the emission rate from plants are neglected, there are no other sources of emission in the test chamber, and the pollutant concentration has first-order loss. All these assumptions are mentioned in the studied articles and justified in Section 2.4.

It is recommended to measure the decay rates in both cases, with and without plants, to estimate the ability to produce a clean air into a certain space. The assumption is governed by this formula ($C_t = C_i e^{-L.t}$), where C_t is a pollutant concentration at time t, C_i is the initial concentration of a pollutant, and L is the decay loss, which is a combination of other losses resulting in ventilation rate, deposition rate, and removal rate by using indoor plants.

The CADR was calculated by using the regression analysis of ANSI/AHAM AC-1-2006 test method; the CADR is calculated as shown in equation (2.1)

$$CADR = V_c(k_t\text{-}k_n) \tag{2.1}$$

Where *CADR* is the clear air delivery rate [m^3/h], V_c is the volume of test chamber [m^3], k_t is the total decay rate with plants [h^{-1}], and k_n is the natural decay rate (without plants) [h^{-1}]. This equation is applicable for articles that provided contaminant decay rates by measuring the concentration versus time for experiments with and without potted plants. In field studies, all the parameters may change; the ventilation rate may vary according to the type of HVAC system; deposition rate varies because of the incoming particles from outdoors, and occupant motion inside indoors, and the pollutant adhesive force on windows and walls. However, the CADR represents the difference between the natural decay rate and the total decay rate. Both have ventilation and deposition rate, but they are cancelled by subtraction.

2.3 The Effectiveness (H)

I created a scenario with a typical office of 75 m^3, to evaluate the effectiveness of indoor plants in a real location. The main assumptions are the following: the number of occupants is 3 person; the office has well-mixed air and a ventilation system with minimum ventilation rate according to the ASHRAE standard 62-2001, and the removal of VOCs via mechanisms other than ventilation is negligible (i.e., negligible all of the infiltration rate, the deposition rate, and the chemical reaction with indoor surfaces and with other indoor air pollutants) to simplify the calculation process and maximize the effectiveness for conservative estimate. The effectiveness of indoor plants is expressed by equation (2.3) (Miller-Leiden et al., 1996)

$$H = 1 - \left(\lambda/(\lambda + \mathrm{CADR/V})\right) \tag{2.2}$$

Where H is the effectiveness of the indoor plants, λ is the air exchange rate [h^{-1}], CADR is the clean air delivery rate [m^3/h], and V is the volume of a typical office [m^3]. ASHRAE Standard 62-2001 was used to calculate the minimum air exchange rate λ for typical office size of 75 m^3. Therefore, the air change per hour is 0.36 [h^{-1}]. Then, the effectiveness is calculated as H = CADR/(CADR+27[m^3/h]). This formula presents a maximum value of H according to an ideal condition since a typical office is chosen with many assumptions.

2.4 The Validation of Assumptions

The assumptions simplify the model equations (2.1 and 2.2) and mostly applicable in laboratory studies. These assumptions should be validated and ensure that the CADR and effectiveness values are representative to indoor plants and indicating their actual implications. However, most of the assumptions are not valid in field studies, which may affect these values. Therefore, the validity of assumptions in field studies are checked as follows:

1. *The indoor air is well mixed.*

This assumption is feasible in laboratory experiments by using a portable fan to circulate the air inside a test chamber. If the air is well-mixed, the samples taken represent the actual average contamination. In a field studies, a well-mixed air can be achieved by adding a portable fan inside a room and turning off the HVAC system or operating HVAC system in fan-only mode.

2. *The indoor environmental conditions remain constant.*

The indoor environmental conditions include air temperature, relative humidity, air pressure, and air density. In laboratory studies, the experimenter maintains these conditions constant by monitoring and adjusting. In field studies, these conditions vary according to occupant activities. Cooking can cause the air temperature to rise, and showering can increase the relative humidity. Using natural ventilations, forced ventilations, air conditioning systems and heating systems affect the indoor air density and temperature. However, this assumption is achievable since no occupants inside the studied rooms or houses while operating the HVAC system for a long time.

3. *There are no other indoor sources.*

The indoor plants were conducted in a sealed chamber and no other indoor sources. However, the indoor plants can omit VOCs from plant leaves and soil (Owen et al., 2001; Yang et al., 2009; Zheng et al., 2010) and microorganisms (Berg et al., 2014; Wolverton and Wolverton, 1993). The microorganisms can help in absorbing and biodegrading the contaminated air. The absorbing of contaminated air can occur in the stomatal openings and on the cuticle wax of the plants leaves and the soil and the rhizosphere region close to the roots where the nutrients and other physiological processes play an important role of contaminant absorptions and biodegradation (further reading about removal mechanisms in (Guieysse et al., 2008)). However, the amount of contaminated air injected into the chamber are much larger than the emissions of other VOCs from leaves, which are not detected by my physical measurements and reported in the articles. Therefore, this assumption may be valid since some of plant emissions and plant itself can reduce the contamination amount. In field studies, this assumption is not valid because of the variety of indoor sources and occupant activities (Baek et al., 1997; Han et al., 2010). Carbon dioxide is produced from smoking and fuel combustion during cooking. Particulate matter contains dust, aerosol, and bioaerosol such as fungi and bacteria. Formaldehyde can be emitted from furniture and wood products (Haghighat and Donnini, 1993). There are two possible ways: to eliminate the indoor sources or to estimate the emissions sources by other means which are out of the thesis interest.

4. *The decay rate follows a first order loss.*

This assumption is valid for laboratory studies since the contaminations that injected into the test chamber were decreasing over the exposure time. The decrease occurs under different mechanisms: by suction through stomatal openings, absorption and biodegradation of plant wax, soil and existing nutrients in the soil, and the deposition on chamber walls. To assess the value of decay rate of the potted plants only, the researcher should present two graphical representations for with and without plants. The difference between the two decays represent the CADR values. In field studies, the reduction of contaminations may not follow the first order loss over time. The fluctuation of contaminant concentrations is affected by the following: the ventilation rate, the deposition rate, and the occupant motion. In addition, the decay rate may be affected by the chemical reaction rates between the VOCs and the physiological processes of the plants. Therefore, the time-average concentrations before and after adding the indoor plants will be an adequate approach, but the CADR equations will be representative under the condition that the final time-averaged concentration is lower than the initial concentration.

5. *The outdoor concentration is not included in laboratory studies.*

The outdoor concentrations were not included in the laboratory studies because of the sealed chambers. In the field studies, the outdoor concentrations should be considered since it varies spatially, seasonally and temporally. In urban communities, the outdoor concentrations are significantly high, and road traffic is a major contributor (Urban air pollution) especially to those who live close to highways. The outdoor concentrations can affect the indoor concentrations through the ventilation system (if the outdoor air is mixed with a return air from HVAC systems) and the infiltration (from the opening windows and doors and housing cracks). At that time, many precautions should be included such as measuring the time averaged outdoor and indoor concentrations, estimating the infiltration and ventilation rates, allocating the inlet airflow through the cracks and fixing them as possible, and estimating the pressure differences through the openings and cracks. If the outdoor air concentrations add more load to indoor air concentration, the CADR equations will not also be valid in that case.

6. Negligible deposition rate or penetration rate through a building/room

Pollutants, including particle and VOCs, can deposit on a surface and penetrate from outdoors through leakage, infiltration, and cracks, and through building walls by radiation (Nazaroff, 2004). The deposition and penetration rates are not negligible in laboratory studies. However, they are canceled by subtraction since they are added to the natural and total decay rates in the CADR equation. That means the CADR value does not change with the variation of penetration and deposition rates. In the field studies, the estimation of the effectiveness depends on the values of these rates, which are discussed in Chapter 4.

In conclusion, I presented a searching method for finding articles that serve the thesis purpose. The methodology focuses on selecting experimental studies that conducted laboratory and field investigations as well as review papers in each category. For the indoor air quality, the selected articles were reviewed in many reviews discussing the removal rates and efficiencies. The formulas of CADR and effectiveness based on a typical room are presented as additional parameters to investigate the impact of indoor plants on indoor air quality. Several assumptions are justified to validate the used equations. The results of using this methodology are presented in the next chapter.

Chapter 3 The Impact of Indoor Plants

This chapter analyzes the impact of indoor plants on indoor air quality regarding to pollutant removal and emissions, energy use, and psychological effects. Each of these categories is reviewed in separate sections.

3.1 Impact of Indoor Plants on Indoor Air Quality

This section focuses on the analysis of experimental investigations of the impact of indoor plants on indoor air quality. It captured 46 articles that experimentally studied the pollutant removal rate by using indoor plants in test chambers such as glass chambers or jars. The main studied parameters are the pollutant (mostly volatile organic compounds (VOCs)) removal rate, the removal efficiency, the decay rates with and without plants, the airflow rate through the test chambers, and the volume of the test chambers, which are not listed in the chapter but in the next chapter. These articles can be classified into two groups: those that measured the removal rate or removal efficiency with and without indoor plants present (12 articles of dark round and black square markers in Figure 3.1) and those that measured a removal parameter only with plants present (34 articles of blank round markers in Figure 3.1). Some of these articles have provided a graphical representation of concentration versus time, and others have provided just numerical values of initial and final concentrations and the exposure time of experiments. A further 10 field investigations in buildings (e.g., not in laboratory chambers) are also included later in this section to provide an insight on the impact of plants on pollutant removal in real buildings.

In general, plants and plant-based air cleaning systems were experimentally tested inside of test chambers in the presence of different types of volatile organic compounds (VOCs), including benzene (Ugrekhelidze et al., 1997; Treesubsuntorn and Thiravetyan, 2012) and formaldehyde (Zhou et al., 2011; Lu et al., 2012; Khoa et al., 2013). As discussed in the previous chapter, the main testing parameters are removal rate and removal efficiency. Indoor plants can experimentally achieve pollutant removal efficiency up to 70-90%. However, in field studies, the findings are mixed. For example, a VOC concentration inconsistently increased after adding indoor plants inside an office building (Kim et al., 2011; Vazquez and Adams, 2014), while in another study, the final VOC concentration decreased in a classroom (Kim et al., 2013). Other factors may contribute to reducing pollutants from indoors, such as natural ventilation compared to mechanical ventilation in a classroom with indoor plants (e.g., Kim et al., 2013), and the additional microorganisms and other materials in the soil (e.g., Wang and Zhang, 2011) (see Chapter 4 for discussion). Also, other studies have shown that indoor plants might be an emission source (Guieysse et al., 2008), this is discussed further in Section 3.2. The mixed findings bring into question the actual ability of indoor plants to remove pollutants.

Using potted plants for the purpose of pollutant removal is often called a botanical filtration system. This system is similar to any other air cleaners for the same pollutant. Therefore, the performance of this system should be evaluated like any air cleaning devices. Three possible test methods are available for evaluation (Kim et al., 2012): the Korean, Korea Air Clean Association (KACA); the Japanese, Japan Electrical Manufacturer's Association (JEMA); and the American, Association of Home Appliance Manufacturer (AHAM) test methods. The difference between test methods is the type of test particles or gas, the size of test chambers, the initial concentration, and the measurement time. Regardless the difference in previous tests, they all use clean air delivery rate (CADR) for the removal of particles, gases, and VOCs (Chen et al., 2005). CADR is used in this thesis to provide an appropriate metric for comparison between botanical filtration system as well as to other types of air cleaners. The CADR is defined as the rate of indoor plants produce clean, purified air to a room or space, and its unit is cubic meter per hour (m^3/h). It is calculated based on the given data found in the 46 articles that mentioned before. Moreover, a scenario is also presented to simulate a typical office with indoor plants as air cleaners, and measure the effectiveness of plants in a real location.

For that reason, the CADR value is evaluated for each article according to different plant species and different contaminants used in the investigation. Figure 3.1 presents the maximum CADR values corresponding to the reference number for the 46 articles that included laboratory investigations. The vertical axis represents the extremely wide range of CADR values from 10^{-6} to 10^3. The details of these values are presented in Chapter 4, and the CADR values are calculated for some articles in Appendix.

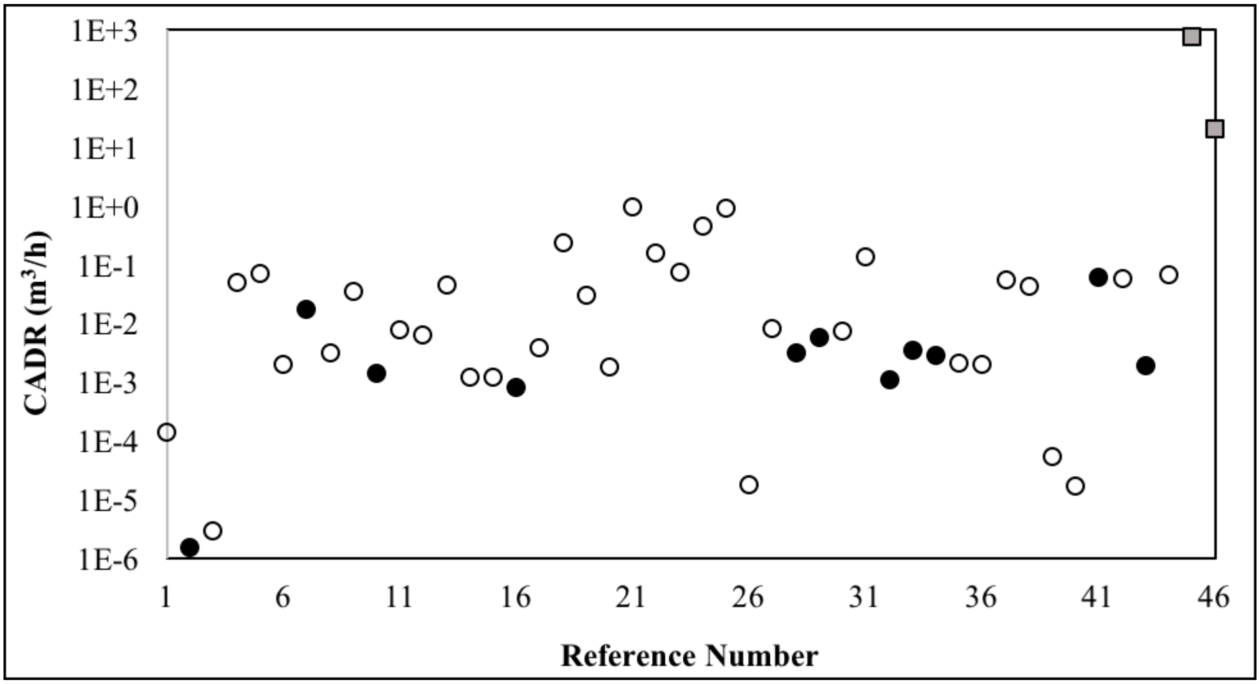

Figure 3.1: The CADR (m^3/h) values with the corresponding citations. The dark round markers refer to the calculated CADR values with and without plants, while the blank round markers refer to the CADR values with plants only (no without-plants studies). The square markers refer to CADR calculated by the authors of articles 45 (with plants only) and 46 (with and without plants).

1. Chun et al., 2010
2. James et al., 2008
3. Saiyood et al., 2010
4. Yang et al., 2009
5. Baosheng et al., 2009
6. Hasegawa et al., 2002
7. Hasegawa et al., 2004
8. Oyabu et al., 2001
9. Oyabu et al., 2003
10. Oyabu et al., 2003
11. Sawada et al., 2003
12. Sawada et al., 2007
13. Aydogan and Montoya,
    2011
14. Collins et al., 2000
15. Cruz et al., 2014
16. De Kempeneer et al.,
    2004
17. Godish and Guindon,
18. 1989
19. Jin et al., 2013
20. Khoa et al., 2013
21. Kim et al., 2011
22. Kim et al., 2010
23. Kim et al., 2009
24. Kim et al., 2008
25. Kim and Kim, 2008
26. Kim and Lee, 2008
27. Kim et al., 2012
28. Liu et al., 2007
29. Mosaddegh et al., 2014
30. Newkirk et al., 2014
31. Orwell et al., 2004
32. Porter, 1994
    Sriprapat and
    Thiravetyan, 2013
33. Tani and Hewitt, 2009
34. Tani et al., 2007
35. Torpy et al., 2013
36. Treesubsuntorn and
    Tiravetyan, 2012
37. Wolverton and Wolverton,
38. 1993
39. Wolverton et al., 1989
40. Xu et al., 2011
41. Xu et al., 2013
42. Lim et al., 2009
43. Yoo et al., 2006
44. Wood et al., 2002
45. Wang et al., 2014
46. Wang and Zhang, 2011;
    Zhang and Wang, 2010

As shown in Figure 3.1, about 95% of the articles, show the CADR values less than or equal to 1 m^3/h. This effectiveness of a botanical air cleaning system with this CADR in a typical room of 75 m^3 and ventilation rate of 0.36 h^{-1} (see Chapter 2) is below 4%. As mentioned earlier, there are two groups: comparison between with and without plant investigations represented in dark markers and only with-plant studies represented in blank markers. The organization of the 46 articles does not flow any specific order except that same researchers are grouped together investigating different plant species under different VOC types. The last three article are placed at the end of x-axis, with two square markers, because of their high CADR values calculated by their authors (Zhang and Wang, 2010; Wang and Zhang, 2011; Wang et al., 2014).

The CADR values for with and without plants are less than that of with plants only, and the CADR values are very small less than and equal to 1 m^3/h for all of the cases. For the CADR below the 1 m^3/h (all articles except 45 and 46), the maximum and minimum values of effectiveness are 3.5 % (Kim et al., 2010) and 5.7×10^{-6} % (James et al., 2008) in the typical room, respectively. That means that in general, the plants have very low CADR compared to other air cleaning devices, including some HEPA filters, which can have a CADR values with a range from 92 to 481 m^3/h as reported in (Waring at al., 2008) and some negative ion generators that can have a CADR values with a range from 27 to 119 m^3/h as reported in (Mølgaard et al., 2014). However, two articles showed higher CADR values in Figure 3.1 that are represented in square markers. Their CADR values are 16.36 m^3/h (Wang et al., 2014) and 756.7 m^3/h (2011 Zhang and Wang, 2010; Wang and Zhang, 2011). Another botanical system called dynamic botanical air filtration (DBAF) system was recently designed and tested by (Wang, 2011), which presented in his dissertation, and published some articles about it (Wang and Zhang, 2010 and 2011; Wang et al., 2014). This system is composed of plants in a growth media enhanced with microorganisms, and a forced air flow through the media. Wang and his research team (Wang and Zhang, 2010 and 2011; Wang et al., 2014) tested DBAF system to remove formaldehyde in a full-scale chamber (265 m^3) and a test chamber (5.12 m^3). The CADR values, calculated by these authors, are 756.7 m^3/h and 16.35 m^3/h for the full-scale and the test chamber, respectively. However, the calculated CADR for one leaf and a whole plant which were 0.086 and 0.161 m^3/h, respectively. That shows the high value of CADR was from auxiliary agents such as high absorbent substances and microorganisms not the plants, which supports the current results (see further discussion about other factors that increased the CADR values in Chapter 4). The effectiveness values of a whole plant and a DBAF system located inside the typical room of 75 m^3 and with a ventilation rate of 0.36 h^{-1} are 6% and 97%, respectively.

Further evidence supports the findings, Chen et al. (2005) tested 15 different air cleaners including botanical filtration system in a steel chamber and under the same operating conditions. The CADR value for a botanical filtration system was 8 m^3/h for some pollutants and almost zero for other pollutants to be removed from the chamber, in contrast with high CADR values of other air cleaners with a range of 25.5 to 600 m^3/h.

In additional to laboratory investigations, the impact of plants on indoor air quality has been investigated in real buildings (Darlington et al., 1998, 2000, 2001; Kim et al., 2013; Kim et al., 2011; Lim et al., 2009; Sawada et al., 2002; Wood et al., 2006; Wolverton and Wolverton, 1996; Vazquez and Adams, 2014). For example, Kim et al. (2011) investigated the VOC concentration including formaldehyde and benzene, toluene, ethylbenzene, and xylene (BTEX), and compared the concentrations with plants to without plants in new and old buildings. The VOC concentrations with plants were higher than that without plants in both buildings. A similar study was done by Wood et al. (2006) in Sydney in two buildings, and it provided the same results. Furthermore, in the United States, Vazquez and Adams (2014) studied the VOC concentration in office buildings. The findings showed that the plants did not reduce the concentration since the concentration substantially increased after six weeks compared to without plant conditions. In addition, a longitudinal quantitative study was conducted by Lim et al. (2009) to examine the concentration of formaldehyde, toluene, ethylbenzene, and xylene and the symptoms of sick building syndrome (SBS) in a group of 82 households of an airtight building in Korea by using indoor plants (42 households with indoor plants and the rest without plants). The measurements are taken in January and July and repeated for another year. The findings showed that the VOCs concentration significantly changed over the season, over a six-month interval, and significantly increased in the second year, although the formaldehyde and toluene concentration decreased for the buildings with plants by 85% and 15% for the first year and reduction by 80% and 18% in the second year, respectively. The reasons for that reduction was by placing four plants in living room, one in the kitchen and three or four in bedroms and controlling the ventilation since the building was air tight. However, there might be other factors contributing to these reductions such as ventilation system, deposition rates, infiltration rate through cracks and openings, environmental change, and changing in personal activities, but was not clear in the study. Overall the field studies have shown different reduction and removal efficiencies compared to the laboratory studies. Although both laboratory and field studies suggest low CADR and effectiveness values.

In conclusion, although the indoor plants can reduce the pollutant concentration up to 90% from laboratory chamber tests, they generally have very low clean air delivery rate (CADR) values below 1 m^3/h, which results in very low effectiveness (below 4%) in a typical indoor environment. Results from field studies generally confirm this finding with minimal concentration reductions associated with plants, other factors may contribute to pollutant reduction with less information about the amount of contribution.

3.2 Possible Emissions from Plants

While plants can absorb some VOCs in chamber tests (e.g., formaldehyde, toluene, and benzene, as mentioned in the previous section), they can also emit other types of VOCs (Owen et al., 2001; Aharoni et al. 2005), microorganisms (Prussin & Marr, 2015), and pollen (Aira et al., 2011), as both of the absorption and emission are part of the biological processes of plants.

The VOCs emission from plants, generally called biogenic volatile organic compounds (BVOCs), can be classified into three major groups: terpenoids, phenolics, and alkaloids (nitrogen-containing compounds). They are involved in ecological functions, such as defense against insects, pollinator attraction, plant-plant communication, plant-pathogen interaction, environmental stress adaptation (Spinelli et al., 2011). Microorganisms are classified into bacteria and fungi. Some of them are useful to plant growth and development including decomposition of organic materials, retaining nutrients in the soil, improving access to water and nutrients from the soil through stem and leaves, and emitting volatile compounds (Jones et al., 2004), and others cause bacterial and fungal diseases (Weber, 1973). Airborne pollen is essential to the reproduction of plants besides other types of pollinations according to plant species. Only VOCs and microorganisms from plants are covered in detail according to the availability of the existing articles.

3.2.1 VOC emissions from plants

The majority of VOCs emitted from plants are in the terpenoids group, which can be classified into four categories: hemiterpene or isoprenoids, monoterpene, sesquiterpene, and other compounds of C>20. They can react with ozone producing harmful byproducts such ad hydroxyl radicals and nitrate radicals (Weschler, 2000). Tropospheric ozone and its byproducts may cause adverse human health effects such as sensory irritation in the upper airway of respiratory system (Wolkoff et al., 2007), aggravate asthma (Kehrl et al., 1999; Trenca et al., 2001), decrements in lung function (Devlin et al., 1991; Kim et al., 2011) and association with increase of mortality (Bell at al., 2005; Jerrett et al., 2009).

Outdoor studies have been conducted to quantify VOC emissions from leaves of different plant species, which can be grouped into leaf-scale studies and ecosystem-scale studies. Examples of leaf and ecosystem-scale studies include investigated VOC emissions from 40 Mediterranean plant species from five different natural habitats (including dunes, macchia, garrigue, forests, and riverside) in Italy, France and Spain (Owen et al. 2001), 20 common plant species in a tropical forest in Costa Rica (Geron et al., 2002), and 13 common plant species in the Mojave and Sonoran Desert region of the western US (Geron et al., 2006). The most dominant BVOCs are terpenoids group such as isoprene, myrcene, α-pinene, β-pinene, limonene, and sabinene. The magnitude of emission rates depends on plant species, temporal, and superficial distributions. There are other branches including atmospheric-chemistry studies, but they are beyond the scope of this review.

However, few indoor studies have been conducted. For example, four ornamented plants have been investigated to quantify VOC emissions (Yang et al., 2009). It was found that total VOC emission was in very small amount and affected by diurnal variation and plant species. The rate of VOCs emission is measured concerning a portion of grams of a substance per 100 g dry weight of plant leaves (100 g dwt) per hour. The rates of VOCs emissions during the day ranged from 430 to 61500 pg/100 g dwt/h according to plant species, while during the night the total emission rates ranged from 130 to 4300 pg/100 g dwt/h for the same species. Terpenoids are the most dominant groups containing sesquiterpenes and monoterpenes, then alcohols, then ketones and esters from plants. In addition, this study continued to explore the VOCs emission from the soil and a plastic pot resulting an average of 130 pg/potted plant/h from the soil, an average of

900 pg/potted plant/h from the surface of plastic pots holding the plants and soil. The VOCs emanated from the growing media, and the plant pots are mostly from microorganisms in the soil and the root exudate such as 2- chlorobenzonitrile from rice root (Kim and Kim, 2000). The results showed that the indoor plants release a negligible amount of VOCs to the indoor air despite the variation of VOCs with respect to plant species.

3.2.2 Microorganisms from Plants

Bioaerosols are ubiquitous indoors as they are transmitted from outdoors through ventilation, and created from animals and human activities. They may consist of the whole microorganism (e.g., bacteria, fungi, and microbial toxin), airborne pollen, and other biological particles. Exposure to mycotoxins from fungal genera, such as *Aspergillus, Cladosporium, Alternaria, Phylloplane*, and *Penicillium*, are associated with irritation, allergy, infectious diseases, acute toxic effects, and respiratory symptoms (Obbrad et al., 2000; Fung and Hughson, 2002; Douwes et al., 2003). In addition, exposure to bacterial toxin species, which include *Staphylococcus aureus*, *Mycoplasma pneumoniae*, *Streptococcus pneumoniae*, *Legionella pneumophila,* and *Mycobacterium tuberculosis,* causes various diseases of respiratory systems such as nose and throat infections, chronic inflammation of the lungs (Legionellosis' disease), and Tuberculosis (Oakley, 1955; Schmitt et al., 1999; Kuhn and Ghannoum, 2003).

Several studies have investigated microorganisms from the plants and their effects on plant and humans. However, few have focused on plants contribution to indoor air quality in residences and greenhouses because there are many contributing sources and it is hard to differentiate them. For example, Torpy et al. (2013) investigated the effect of plant existence on the fungal spore load in two seven-storey-office building in Sydney, Australia. The number of the pots varies from one pot to three pots per office. They found that the total counts of airborne fungal spore samples collected from offices with plants ranges from about 50 cfu/m^3 to 130 cfu/m^3 and slightly higher than that offices without plants (about 60 cfu/m^3), while the outdoor fungal spore was estimated about 570 cfm/m^3 in autumn and 320 cfu/m^3 in spring. The counts for *Cladosporium*, *Alternaria*, and *Penicillium* fungal genera were ranked the highest fungal species but dramatically lower than that of outdoors. Another example, Lehtonen et al. (1993) took some measurements of microbial counts, not the emission rates, to quantify the fungal spore concentration in seven dwellings in central Finland. These measurements considered individual activities (e.g., sweeping, cooking, changing mattress sheets), pets and houseplants into consideration. The fungal spore concentration from houseplants was 70-150 cfu/m^3, which was substantially smaller than that of other activities. Another comparison was performed between sunny rooms and low-light rooms each has two cases, filled with interior plants and no-plants, in order to evaluate the loads of microorganisms to the indoor air (Wolverton and Wolverton, 1996). It was found that the counts of airborne bacteria and molds for the sunny room was almost half the amount of the bacterial and mold counts in the low-light rooms.

Legionella pneumophila is a thin aerobic, gram-negative bacterium of the genus *Legionella*, and it is a primary human pathogenic bacterium which causes Legionnaires' disease (Hampton et al., 2016). This species can be found in man-made water systems and water tap (Silk et al., 2012). Since a biofilter uses tap water for irrigation, it is necessary to investigate whether the biofilter contributes to the production of this bacterial species (Legionella pneumophila) and other microbial into the indoor environment. Mallany et al. (2000) measured the concentration of fungal spores and bacteria by using a biofilter in a meeting room and introducing *Legionella pneumophila* to the biofilter to test its effect on the proliferation of *L. pneumophila*. The experiments were performed to measure microbial concentration through the intake air from a certain room to the biofilter, the exhaust air from the biofilter to the room, and the watering system, which was directly taken from an aquarium of the hydroponic system through low pressure misting lines. The fungal spore concentration was observed in the range of 18 to 58 cfu/m^3 and bacterial concentration ranged from 75 to 300 cfu/m^3, while a reference room without a biofiltration system showed higher values since the fungal spore and bacteria concentrations ranged from 30-130 cfu/m^3 and 150 to 520 cfu/m^3, respectively. *Legionella pneumophila* was undetectable (less than 1 cfu/m^3). The presented results showed that the bacterial loads, including the loads of *Legionella pneumophila,* from indoor plants in residential houses were negligible.

However, there may be greater concern about plant emissions in indoor environments with a high density of plants according to gardening activities. For example, Burge et al. (1982) investigated the fungal spore concentration in 17 greenhouses, each contained more than ten house plants. The investigation occurred three times; during a recirculating fan operation, before and during plant watering. The plants were watered close to the surface of soil without wetting the leaves, it was found that the total fungal spores were 1650, 3011 and 2221 cfu/m^3 for before watering, during watering and during fan operation, respectively. The predominant fungal genera were *Cladosporium, Penicillium, Aspergillus,* and *Alternaria*. Also, the total particles in the greenhouse were 250, 600, and 250 particles/m^3 before watering, during watering and outdoors, respectively. These total particles included the most dominant taxa such as pollen, *Alternaria*, *Perconia*, *Epicoccum*, *Pithomyces*, and *Algae*.

Another example, Li and LaMondia (2010) studied the bioaerosol concentration in two different greenhouse structures that specialized in the growth of ornamental plants at two different locations and different operating conditions. The difference in the structure and operating conditions affected on the microbial load since adding an exhaust fan to suck the indoor contaminated air and using modern structure as in the first greenhouse rather than wooden structure as in the second greenhouse reduced the microbial loads from the indoor plants. The total fungal spore concentration was 9233 spore /m^3 and 5053 spore/m^3 in the first and second greenhouse, respectively. The predominant fungi were fungal genera of *Trichoderma, Aspergillus*, *Penicillium,* and *Cladosporium*, hyphal fragments and yeast-like. However, the overall average concentrations for the outdoor airborne fungi were 853.9 spores/m^3. In addition, the concentration of thermophilic actinomycetes ranged from 35 to 315 cfu/m^3, while the concentration of thermophilic bacteria ranged from 35 to 385 cfu/m^3, and there was no significant increase during watering or fan operating. Similarly, Rodolfi et al. (2003) collected airborne fungal spore from a tropical greenhouse in a botanic garden. The averages of fungal spore concentrations ranged from 1158 to 1502 cfu/m^3. Therefore, the microbial concentrations in greenhouses are significantly higher than that in residences. That is likely because of the large amount of plants in the greenhouses.

In general, plants emit a wide range of volatile organic compounds and microorganisms. The overall concentrations depend on the number of indoor plants, special and temporal variation, and watering systems. The dominant groups of VOCs are terpenoids, alcohols, ketones, and esters, while the dominant fungal genera are *Cladosporium, Penicillium, Aspergillus,* and *Alternaria*. The bacterial communities were not classified into genera nor species through the mentioned studies. Many studies focused on emission from plants to outdoor environments but limited related to indoor places. The VOC emission rates from the indoor plants are limited.

Also, the loads of microorganisms from indoor plants are less than that from other indoor sources. Both of the emissions can be increased according to the increase amount of indoor plants and during the planting process. Better ventilation helps reducing the load of emissions.

3.3 Impact of Plants on Energy Use

In the previous section, I analyzed the ability indoor plants regarding pollutant removal and the effect of their emissions, which showed that they have minor effect compared to other alternatives. In this section, the investigation is extended to include the impact of plants on energy use. Plants have been used outdoors as vegetated cladding of buildings, which are considered as greenery systems. There are three major types of greenery system, which are green facades, green walls, and green roofs.

Many investigations have been conducted on greenery systems in laboratory and field studies. The studies have shown that the greenery systems can experimentally reduce heat transmission through building structure, which leads to up to an average of 20% energy savings of air conditioning systems under hot and dry conditions in a model building (Rodgers et al., 2012; Chen et al., 2013; Cameron et al., 2015). In addition, there are many literature reviews related to greenery systems, which have different trends (see Chapter 1, the summary of previous literature reviews). However, the field studies were not included in previous reviews, and the connection between indoor conditions and greenery systems needs more investigation to assess the impact of using greenery systems on a whole building, which is our focus in this section.

The method of analysis in this section is quite similar to Section 3.1. The current method is to capture all the related scientific articles of greenery systems from 2010 to 2016 in order to analyze the effect of greenery systems on indoor conditions. This period of investigation was selected because most of the previous review articles have mostly covered before this period and up to 2013 (see Chapter 2 Methodology). There are 32 articles until 2016 organized in reverse chronological order, as shown in Table (3.1 and 3.2). Table 3.1 provides basic information mentioned in articles: types of greenery systems, location and environment, type of study, season, providing a comparison to without plants, and parameters, each of which is discussed, while Table 3.2 provides the basic findings for each article

The given information is analyzed in Tables 3.1 and 3.2 divided into three general areas. First, the general information is collected about the studies and plants in each study. Second, the studied parameters are summarized including the outside parameters, inside parameters, energy, and other necessary parameters. Finally, the results are tabulated in Table 3.2 for each article.

In the first group, I classified the studies according to the type of greenery systems used, the locations of the conducted study, the space, and the type of the conducted studies, as shown from Table 3.1. There are two articles for green roofs, nine for green facades, 19 for living or green walls, one for a biowall and one for potted plants. For the location of studies, the majority of studies were conducted in Europe (15 articles), especially Spain and Italy, followed by Asia (8 articles), North America (2 articles), South America (1 article), and Africa (1 article). The study space was also considered, such as buildings (15 articles including houses schools, and offices), and room models (5 articles), and standing-alone walls (8 articles). For the type of study, there are four main types including experimental studies (18 articles), field measurements (9 articles), simulation (6 articles), mathematical modeling (2 articles), and experimental and field measurements investigation (5 articles). That shows the variety of the investigations conducted during the six years.

In addition, the period of conducted investigations was also considered, as in Table 3.1. The previous articles can be classified into during the summer season (15 articles), in a whole year (7 articles), five articles in the winter season (5 articles), and few in other season. Pérez et al. (2011) presented a whole-year study. Moreover, Scarpa et al. (2014) investigated between two seasons, summer and winter. However, Carlos (2015) and Cameron et al. (2015) investigated experimentally and computationally the performance of the systems only in winter.

Moreover, the difference between two cases was also observed. There are only 24 articles, which have provided a comparison between a building structure with and without greenery systems. Without greenery systems refers to the bare building envelopes (e.g., bare walls and bare roofs). This comparison is useful in understanding and estimating the effect of adding greenery systems on the building structures.

Table 3. 1: Organization of previous research articles from 2010 to 2016 (32 articles)

References	**Types of greenery systems**	**Location**	**Space**	**Types of study**	**Season**	**W/O plant**	**Parameters**			
							Outside (T_o - RH_o – SR – WS - T_{se})	**Inside** (T_{si} - T_i - RH_i)	**Energy**	**Others**
Coma et al. (2016)	GR	Spain	Cuboids	E	Year	Yes	(√ - √ - √ - 0 - √)	(√ - 0 - 0)	ES	
Cameron et al. (2015)	GF	UK	Cuboids	E	Winter	Yes	(√ - 0 - 0 - 0 - √)	(√ - 0 - 0)	ES	
Carlos (2015)	LW	Portugal	Building	S	Year	Yes	(√ - √ - √ - √ - 0)	(0 - 0 - 0)	ES	
Bolton et al. (2014)	GF	UK	Building	E and F	Maritime	Yes	(√ - 0 - 0 - 0 - √)	(√ - √ - 0)	ES	
Coma et al. (2014)	GF	Spain	Cubicles	E and F	Summer	Yes	(√ - 0 - √ - 0 - √)	(√ - √ - 0)	ES	
Feng and Hewage (2014)	GR, LW	Canada	Building	S	Year	No	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	HR	Financial assessment
Feng and Hewage (2014)	LW	Mediterranean countries	Building	S	Year	No	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	Balance, emission
Haggag et al. (2014)	LW	UAE	School	F	Summer	Yes	(0 - 0 – 0 - 0 - √)	(√ - √ - 0)	ES	
Malys et al. (2014)	LW	Switzerland	Wall	E and M	Spring	No	(√ - √ - 0- 0 - 0)	(0 - 0 - 0)	HR	Plants performance
Mangone et al. (2014) Mangone and van der Linden (2014)	PP	The Netherlands	Office	QE	Year	Yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - √)	ES	Thermal comfort
Olivieri et al. (2014) ^{2}	LW	Spain	office	E	Year, Sum	Yes	(√ - √ - √- 0 - √)	(√ - √ - 0)	HR	
Pulselli et al. (2014)	LW	Italy	Building	S	Summer	Yes	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	Emergy
Scarpa et al. (2014)	LW	Italy	Wall	M	Sum-Win	No	(√ - √ - √- 0 - √)	(√ - 0 - 0)	---	
Tan et al. (2014)	LW	Singapore	Walls	F	Monsoon	Yes	(√ - √ - 0 - 0 - √)	(√ - 0 - 0)	---	Radiant temp.
Chen et al. (2013)	LW	China	Models	E	Summer	Yes	(√ - √ - √ - 0 - √)	(√ - √ - 0)	ES	
Jaafar et al. (2013)	LW, GF	Malaysia	Building	E and F	Summer	No	(√ - √ - √ - √ - 0)	(√ - 0 - 0)		
Mazzali et al. (2013)	LW	Italy	Walls	E	Summer	Yes	(0 - 0 - √ - 0 - √)	(√ - 0 - 0)	HR	
Nadia et al. (2013)	LW	Algeria	Cuboid	E	Summer	Yes	(√ - 0 - 0 - 0 - √)	(√ - 0 - √)		
Susorova et al. (2013)	GF	US	Building	F and M	Summer	Yes	(√ - √ - √ - √ - √)	(√ - 0 - √)	HR	
Tseng et al. (2013)	LW	Taiwan	Wall	F and S	Year	Yes	(0 - 0 - 0 - 0 - √)	(0 - √ - 0)	ES	
Varini (2013)	LW	Colombia	Room	S	Summer	Yes	(√ - 0 - 0 - 0 - √)	(0 - √ - 0)	---	
Fernandez-Bregon et al. (2012)	LW	Spain	Walls	E	Spring	Yes	(0 - 0 - 0 - 0 - √)	(0 - 0 - 0)	---	Pressure sound
Fernandez-Canero et al. (2012)	LW	Spain	School	E	Summer	No	(√ - 0 - 0 - 0 - 0)	(0 - √ - √)	ES	

Rodgers et al. (2012)	BW	US	House	E and F	Summer	No	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	
Pérez et al. (2011)[2]	GF	Spain	Building	E	Year-Sum	Yes	(√ - √ - √ - 0 - √)	(0 - 0 - 0)	---	Illuminance
Perini et al. (2011)	GF, LW	The Netherlands	Walls	F	Summer	Yes	(√ - 0 - 0 - √ - √)	(0 - 0 - 0)	---	
Sunakorn and Yimprayoon (2011)	GF	Thailand	Shopping mall	E and F	Summer	Yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - 0)	---	Indoor air velocity
Cheng et al. (2010)	GF	Hong Kong	Office	E	Summer	Yes	(√ - √ - 0 - 0 - √)	(√ - √ - 0)	HR	
Wong et al. (2010)	GF, LW	Singapore	Walls	E	Monsoon	Yes	(√ - 0 - 0 - 0 - √)	(√ - 0 - 0)	---	

Table 3.2 a: Results from previous research related to Table 3.1

References	**Building Envelope U ($W/m^2.K$)**	**Outdoor Environment**		**Microclimate**		**Indoor conditions**	**Results**
		T_o (°C)	**RH_o (%)**	**TR_{ex} (°C)**	**TR_{in} (°C)**	**T_i (°C) or RH_i (%)**	**ES (%) or HR(%)**
Coma et al. (2016)	Concrete $U_{w/p}$= 0.79 to 1.4 $U_{w/o}$= 0.71 IS	4 to 24	51 to 80	---	0.5 to 1	18 and 22	ES: 2 - 19 ↓
Cameron et al. (2015)	Brick	ave 2	---	-1.3	---	---	ES: 30 ↓
Carlos (2015)	Only support $U_{w/p}$= 0.37 $U_{w/o}$= 2.15-3.25	2 to 24 ave 4	55 to 90	---	---	---	ES: 10 ↓
Bolton et al. (2014)	Brick, $\mathbf{U_{w/o}}$= 4.18	-2.2 to 17.4	---	3.1	0.1	20	ES: 8 ↓
Coma et al. (2014)	Concrete	15 to 35	---	10	-0.5	24, 14 to 20 Δ_t = +0.2 ↓	ES: 1, 5.5 ↓ cumulative
Feng and Hewage (2014)	NA $U_{w/p}$= 0.32	-7 to 20	---	---	---	17-27	HR: 0.6 -5.4 GR ↓ 2.1-8.4 LW ↓
Feng and Hewage (2014)	Only support	---	---	---	---	---	ES: 1.2 to 43 ↓
Haggag et al. (2014)	Concrete	35 to 50 sum 25 to 35 win	---	7	6	47 w/p, 55 w/o Δ_t = +8 ↓	ES: 20.5 ↓
Malys et al. (2014)	Brick	7 to 15	50 to 95	5 to 10 3 to 7	---	---	---
Mangone and van der Linden (2014)	Wall assembly, $U_{w/o}$= 0.14 to 0.35 IS	25 to 27	---	---	1.1 to 2	25 to 28 w/p	ES: 2.9 to 9.5 ↓
Mangone et al. (2014)	NA	< 5	---	---	---	21.5, 22 RH_i: 42.71 9.7% comfort high	---

Table 3.2 b: Results from previous research related to Table 4…continued

References	**Building Envelope U (W/m^2.K)**	**Outdoor Environment**		**Microclimate**		**Indoor Conditions**	**Energy Saving**
		T_o (°C)	**RH_o (%)**	**TR_{ex} (°C)**	**TR_{in} (°C)**	**T_i (°C) or RH_i (%)**	**ES (%) or HR (%)**
Olivieri et al. (2014)	NA, $U_{w/o}$= 0.33 IS $U_{w/p}$= 0.37 IS	20 to 30 sum 4 to 8 win	20 to 40 sum 60 to 80 win	15 -2 to 0	8 to 11 2 to 7	$\Delta_t = +2$ to 10 ↓	---
Olivieri et al. (2014)	NA, $U_{w/o}$= 0.33 IS $U_{w/p}$= 0.37 IS	ave 25.1	27 to 57	ave 7	ave 8	23.2 w/p, 27.4 w/o $\Delta_t = +4$ ↓	HR: in 93 ↓ out 98 ↓
Pulselli et al. (2014)	Bricks $U_{w/o}$= 0.21 IS, 1.13	---	---	---	---	---	ES: 6.2 to 15.2 ↓
Scarpa et al. (2014)	Concrete, brick	---	---	---	---	---	---
Tan et al. (2014)	Concrete	23 to 32	ave 76	9	0.5	---	---
Chen et al. (2013)	Brick $U_{w/p}$= 0.25	28 to 46	45 to 98	21	max 7	37 w/p, 38.5 w/o $\Delta_t = +1.5$ ↓	ES: 12 ↓
Jaafar et al. (2013)	Only support	24 to 46.7	ave 70.2	---	1	RH_i: 70-72 Δ_r = ave 2 ↑	---
Mazzali et al. (2013)	Concrete	---	---	1 to 20	---	---	HR: in 13-70 ↓ out 3-80 ↓
Nadia et al. (2013)	Brick, Concrete	28 to 57	---	0.8	21	RH_i: 41.5 w/p 47.4 w/o $\Delta_r = +6$ ↓	---
Susorova et al. (2013)	Brick, $U_{w/o} = 4$ $U_{w/p} = 2.5$	22 to 38.8	55 to 83	1.2	0.6	---	HR: 14 to 43 ↓
Tseng et al. (2013)	Concrete	---	---	2.2	---	22.3 w/p, 23.9 w/o $\Delta_t = +1.6$ ↓	ES: 7 to 10 ↓
Varini (2013)	Brick	24 to 32	---	5.5	---	$\Delta_t = +1.8$ to 6 ↓	---
Fernandez-Bregon et al. (2012)	Concrete	10.9 to 21	---	5	---	---	---
Fernandez-Canero et al. (2012)	Only support	18 to 36	---	---	---	w/p: 19-22 w/o: 21-26 $\Delta_t = +4$ ↓	ES: 20 ↓
Rodgers et al. (2012)	NA	---	---	---	---	---	ES: 27 ↓
Pérez et al. (2011)	NA	7 to 33	25 to 65	5.5 to 15.8	---	---	---

Table 3.2 c: Results from previous research related to Table 4…continued

References	Building Envelope U ($W/m^2.K$)	Outdoor Environment		Microclimate		Indoor Conditions	Energy Saving
		T_o (°C)	RH_o (%)	TR_{ex} (°C)	TR_{in} (°C)	T_i (°C) or RH_i (%)	ES (%) or HR (%)
Pérez et al. (2011)	NA	20 to 32	ave 44	7 to 15.2	---	---	---
Perini et al. (2011)	Brick and plywood	13 to 32, ave 16	---	2.7 GF 5 LW	---	---	---
Sunakorn and Yimprayoon (2011)	NA	ave 34.25 ave 32	---	---	---	w/p: 28-33 w/o: 27-36 $\Delta_t = +1.65$ to 4 ↓	---
Cheng et al. (2010)	Concrete	ave 26.4	ave 75	2 to 16	1	25.2	HR: 85 ↓
Wong et al. (2010)	Concrete	25 to 34	---	7 to 12	---	---	---

Types of Greenery systems: GR … Green Roof, LW … Living Wall, GF … Green Façade, PP … Potted Plants, BW … BioWall. **Location:** country name. **Types of study:** E … Experimental, Q … Quasi, S … Simulation, M … Mathematical modeling, F … field measurement. **Season:** Sum … Summer, Win … winter, Year … whole year. **Parameters:** outside: (T_o outdoor air temperature – RH_o outdoor relative humidity – SR solar radiation – WS wind speed – T_{se} external wall surface temperature); insides: (T_{si} internal wall surface temperature – T_i indoor air temperature – RH_i indoor relative humidity) ; **Energy:** ES … energy saving, HR … heat flux reduction. NA…not available. U … overall thermal conductivity through walls. **Results:** TR… temperature reduction, RH … Relative humidity. **Results:** IS...insulated, ave…average value, max…maximum value, Δ_t … indoor temperature difference, Δ_r …indoor relative humidity difference, w/p… with plants, w/o…without plants, ↓ … reducing, ↑ … increasing, +ve… decreasing, -ve…increasing.

Superscript: 2 … two articles. **Subscript:** ex… external walls, in…internal walls, w/p… with plants, w/o…without plants.

The second group of the studied parameters, the majority of research focused on the vegetated structure. The microclimate parameters can be divided into outside and inside parameters. Outside parameters are the outdoor or ambient temperature and relative humidity, the solar radiation, the wind speed, the vegetation temperature, and the external wall surface temperature. Inside parameters are the inside wall surface temperature, the indoor air temperature, and the indoor air relative humidity.

For the outside parameters, as shown in Table 3.1, the majority of articles were concerned about the outdoor conditions: ambient air temperature and ambient relative humidity. However, other outdoor parameters, such as relative humidity, solar radiation, and wind speed were rarely covered (about ten, nine, and four articles, respectively). The external wall surface temperatures were investigated in 18 articles. Six articles have studied the outdoor air temperature, the outdoor air relative humidity, and the external wall surface temperatures, altogether. For inside parameters, the inside wall temperatures were measured in half of the existing articles (14 articles), in comparison to the indoor air temperature and indoor air relative humidity, which were less measured in eleven articles and three articles, respectively. In addition, heat flux (HR) and energy consumption (ES) were studied in thirteen articles and five articles, respectively. The heat transfer reduction represents the reduction value of the total heat transfer through the building enclosure (walls and roofs), while the energy saving (ES) represents the reduction or saving in the energy consumption of the entire building or the HVAC system used in the model building. Furthermore, other parameters also were included, such as financial assessment (Feng and Hewage, 2014), Energy balance and emissions (Feng and Hewage, 2014), the performance of plants (Malys et al., 2014), emergy, which is environmental accounting method that evaluate the energy consumed in direct and indirect transformations (Pulselli et al., 2014), radiant temperature of outdoor air (Tan et al., 2014), sound pressure (Fernandez-Bregon et al., 2012), illuminance (Pérez et al., 2011), and the indoor air velocity (Sunakorn and Yimprayoon, 2011).

The third group is to analyze the results obtained from these articles, which are presented in Table 3.2a, 3.2b and 3.2c. The results are categorized into five themes: building structure, outdoor environment, changes in microclimate conditions, indoor conditions, and energy savings.

a) *Building Structure*:

The building envelope was constructed of concrete or brick. As shown in Table 3.2a, few studies stated the thermal conductivity for the building envelope with greenery systems (5 articles), and of the bare envelopes (7 articles). The thermal conductivity for uninsulated, bare walls and roofs has a range of 1.13 to 4.18 $W/m^2.K$ and for insulated walls has a range of 0.14 to 0.35 $W/m^2.K$ (Mangone and van der Linden, 2014; Olivieri et al., 2014; Pulselli et al., 2014) and an insulated roof of 0.71 $W/m^2.K$ (Coma et al., 2016). For vegetated envelopes, we can find that the thermal conductivity can range from 0.32 to 0.37 $W/m^2.K$ for green walls and 0.79 to 1.4 $W/m^2.K$ for green roofs. That means the climbing plants add thermal resistance to the uninsulated wall and roof structure resulting in reducing the overall thermal, and they can reduce the amount of heat transfer through vegetated walls and green roofs. However, the reduction of thermal conductivity may vary for the case of insulated building structure as well as the change of the weather, which will be discussed in Chapter 4.

b) *Outdoor Environment Conditions:*

Both outdoor air temperature and relative humidity were measured in 11 articles. According to the locations, there are low average values of air temperatures in winter seasons (e.g., 2°C, 4°C, and 9°C), and high ranges of temperatures referred to summer seasons from 25°C to 50°C. The relative humidity varies according to the precipitation amount and has two levels: low level or dry to moderate weather from 25% to 50%, and high level of precipitation from 50% to 90%. The solar radiation varies from 230 W/m^2 (Cheng et al., 2010) to 750 W/m^2 (Nadia et al., 2013; Tan et al., 2014).

c) *Microclimate Conditions:*

The microclimate conditions refer to temperature differences of external and internal wall surfaces between envelopes with and without vegetation. The external surface temperature reduction (TR_{ex}) is the difference between external surface temperatures of bare surfaces and vegetated surfaces behind the plants and the growing media if exists. The internal surface temperature reduction (TR_{in}) is the difference between internal surface temperatures of bare surfaces and vegetated surfaces. This comparison will demonstrate the effect of using greenery systems on energy saving due to the temperature reduction. The circumstances vary according to the building envelope, the location of the system, the variation of environmental conditions, and the greenery system designs, which leads to variation in values of temperature reduction for both external and internal surface temperatures.

As shown in Table 3-a and b, the temperature reduction for external surfaces varied between -2°C to 15°C (Olivieri et al., 2014) and 5.5°C to 15.8°C (Pérez et al., 2011) over the year because of the change in weather and the fluctuation of solar radiation. This reduction was significant in studies without human occupancy. However, in a field study with human occupancy, Tseng et al. (2013) observed that the external temperature reduction was 2.2°C during the year by applying a large vertical garden on one wall. For the internal surfaces, the temperature reduction changed based on the location of greenery system and the occupancy number; for empty places, 0.5°C to 1°C for green roofs (Coma et al., 2016), 2°C to 11°C to for living walls (Olivieri et al., 2014). Mangone et al. (2014) investigated the use of potted plants inside an office with occupants resulting in reducing the internal surface temperature by 1.1°C to 2°C.

a. Winter season

During the winter season, we can find that the external temperature reduction (TR_{ex}) was -1.3°C (Cameron et al., 2015), the negative value means that the green wall is wormer than the bare wall. That means the wall surface behind the vegetation is warmer, and the vegetation acts as insulation and protects the wall from the cold weather, and the overall thermal conductivity of the vegetated wall is less than the bare wall resulting in saving heating load during cold weather. Unfortunately, this was the only article that focused on the investigation in the winter season and showed external temperature reduction. In Maritime season, the outdoor air temperature ranged from -2.2°C to 17.4°C (Bolton et al., 2014), the temperature reduction was an average of 3.1°C for external surfaces and of 0.1°C for internal surfaces. The use of vegetated walls helped damp the oscillation of surface temperature and relatively increased wall temperature in freezing weather, as well as decreased wall temperature in high ambient temperature compared to bare walls the corresponding weather.

b. Spring and summer season

During spring and summer seasons, the solar radiation and the ambient air temperature significantly raise resulting in increasing the external surface temperature more than the outdoor air temperature by about 5 to 10°C due to the high absorptivity of the construction material. It was obvious that the temperature reduction for the external surfaces was higher than that of other seasons with a range from 2°C to 20°C. The high values were related to the exposure to peak solar radiation, which was absorbed by plants, and occurred during between 14 to 16 solar hour. The low values were related to the reduction during the night or cloudy days. The majority of internal surface temperature reduction was about 1°C. There are three high values: 6°C (Haggag et al., 2014), 7°C (Chen et al., 2013), 21°C (Nadia et al., 2013) based on a room model. The reason for that, the design of experimental space was tight, mostly without windows, insulated space, and without occupation, which exposed to extremely high outdoor air temperature more than 45°C.

d) *Indoor Conditions:*

Indoor conditions were mostly indoor air temperature and relative humidity. The indoor air conditions can be divided into air-conditioned and unconditioned spaces. For the air-conditioned space, as shown in Table 5, the indoor air temperature has two levels: constant at different setting temperatures and free floating temperature. First, the constant temperatures have different values, such as 18°C, 22°C, 24°C, and 25.2°C. The thermal comfort of an office with indoor plants was improved by 9.7% compared to an office without plants (Mangone et al., 2014) based on the mean predicted votes of satisfied occupants. Second, the free floated temperatures have different ranges, such as 14°C to 20°C (Coma et al., 2014) with a reduction of 0.2°C, 17°C to 27°C (Feng and Hewage, 2014), 25°C to 28°C (Mangone et al., 2014), 23.9°C with a reduction of 1.6°C with green walls (Tseng et al., 2013), and 19°C to 22°C and 21°C to 26°C (Fernandez-Canero et al., 2012) with a reduction of 4°C.

For unconditioned space, two indoor conditions were compared when the door of the studied space was opened and closed. A space with a green façade covering a window caused the indoor air temperatures changed from 27°C to 36°C without plants to 28°C to 33°C with green façade by a decrease of 1.65°C to 4°C (Sunakorn and Yimprayoon, 2011). For the rest of studies, the indoor temperature reduction was varied according to room size and weather conditions. Haggag et al. (2014) measured the indoor air temperature inside an unconditioned school. They found that the temperatures would be 55°C without plants and dropped to 47°C with living walls since the outdoor air temperature ranged from 35°C to 55°C in summer. Still, the use of air conditioning systems is essential since the indoor air temperature is above the comfort zone (22°C to 26°C).

In the arid and hot climates, the use of living walls dropped the indoor air temperature to 37°C by a difference of 1.5°C compared to the bare walls (Chen et al., 2013). This temperature reduction is not sufficient to make the occupants feel thermally comfortable since the temperature is out of the range of 22 to 26°C for thermal comfort. However, in moderate climates, the outdoor air temperatures have a maximum value of 30 or 32°C, and the indoor air temperature is reducing by 2°C to 10°C and 4°C (Olivieri et al., 2014), and 1.8°C to 6°C (Varini, 2013), which is likely to provide thermal comfort to the occupants.

According to indoor relative humidity, the measured values were 42.71% (Mangone et al., 2014) for a conditioned space, 70% to 72% with increased average value of 2% by using plants (Jaafar et al., 2013), and 47.4% with difference of 6% by using plants (Nadia et al., 2013). The variation of these values depends on the watering process and the evapotranspiration process of plants, and the studies were performed in unconditioned space.

e) *Energy Savings:*

The energy saving relies on the heat reduction through the envelope and the savings in energy consumption of the building or the studied room. Since there was temperature reduction through walls and environmental conditions, energy saving achieved in most studies with a range of 2% to 40%. The variation of results depends on the percentage of green coverage, the weather conditions, and the system design.

Buildings with green roofs consume less energy by 2-19% (Coma et al., 2016) and have less heat transfer by 0.6-5.4% (Feng and Hewage, 2014) than that of bare roofs of a model house. However, the retention of moisture content may increase the indoor relative humidity, which was not measured in their research. Also, the reduction of energy consumption was less in winter than other seasons by a range of 0.6% to 2% according to the portion of the vegetated area of the walls. For a building with green facades, the energy saving was 5.5% to 30% for different seasons and can reach to high heat transfer reduction by 85% compared to a bare wall (Cheng et al. (2010) while less saving during winter seasons (Bolton et al., 2014; Cameron et al. 2015). For green walls, the average of building energy saving was more than 10%, while the range is from 1.2 to 43%. In addition, most plant species used in research are evergreen and deciduous plants since they affect the heat transfer reduction by the percentage of vegetation coverage.

In comparison between greenery systems, Feng and Hewage (2014) compared green roofs to living walls and found that the heat transfer reduction between green roofs and bare roofs (0.6 to 5.4%) is less that the heat transfer reduction between living walls and bare walls (2.1 to 8.4%). Additionally, the heat flux reduction were 93 % and 98% for green roofs and living walls, respectively (Olivieri et al., 2014), and more than that of the green façade (85%) (Cheng et al., 2010). Other moderate heat reduction values include incoming (13 to 70%) and outgoing heat reduction (3 to 80%) for living walls (Mazzali et al., 2013), and 14 to 43% for green facades (Susorova et al., 2013). The reason for this reduction is due to the absorptivity value of evergreen plants (0.4 to 0.6) to absorb and intercept solar radiation and the mitigating effect from the evapotranspiration process (Hunter et al., 2014).

Also, two articles have studied the greenery systems with occupants (Tseng et al., 2013; Mangone and van der Linden 2014). Mangone and van der Linden (2014) applied a green canopy to cover courtyard inside a building. They found that the green shading annually saved energy consumption by a maximum of 9.5% and varied according to the occupation load inside the building. In addition, Tseng et al. (2013) were testing a new sensor platform to measure the energy saving of an occupied building with a massive vertical garden. The results showed that the vertical garden saved about 7 to 10% daily and 1.5 % annually of the total energy consumption of the whole building.

Together, these results provided some important points listed as the following: one, using plants as insulation can lower the temperature difference across the building envelope, which lead to decrease the heat flux through the construction. Two, plants absorb and intercept solar radiation which also leads to a lower surface temperature. Three, the thermal conductivity of vegetated structure is less than that of bare structure, while adding an insulation layer may reduce the effect of the vegetated structure on its thermal load compared to the insulated structure without vegetation. Four, few studies have focused on the correlation of greenery systems and human occupancy, since there are two studies have discussed this issue. Five, many studies have overlooked the indoor relative humidity, which may increase due to the evapotranspiration and irrigation processes. Finally, using plants cannot substitute air conditioning systems under any circumstances, although plants reduce surface temperature difference through the construction.

3.4 Impact of Indoor Plants on Psychological Status

Third, indoor plants have psychological and physiological benefits according to common theories in human psychology (Kaplan & Kaplan, 1989; Ulrich et al., 1991), such as improving productivity and concentration (Bringslimark et al., 2007), stress reduction (Wassenberg et al., 2015), lowering blood pressure, and improving health and wellbeing (Park and Mattson, 2009).

The experimental design, which refers how participants are allocated to the different conditions (or independent variable groups) in an experiment, shows the statistical significance of the psychological benefits of indoor plants among the groups. The issue here is that the experimental design did not sufficiently generalize these benefits by including huge population size. That means there are other confounding factors underlying the conducted experiments affect the outcomes (Bringslimark et al., 2009).

The main purpose of this part is to investigate the psychological benefits of indoor plants by analyzing previous studies. In the beginning, two definitions are needed to understand this field; psychology is defined as “the scientific study of mind and behavior” (Stangor, 2010); and perception is the process of perceiving something with sense or the state of being aware of something. The author has used these terms interchangeably according to the research context to express about any interaction occurred between occupants and indoor plants, which appeared in mind and behavior.

To show the effect of indoor plants, a researcher establishes two groups: control group without plants and experimental group with plants. The subjects or participants enter separately the control and experimental rooms without repetition, which is called between-subjects design. The researcher performs the required measurements before, during, and after the experimental period, whose process is so-called repeated measures. If the participants are exposed to two or multiple cases and one of them is the control or a reference case, the design is called within-subjects design. To assure the internal validity of research, a researcher randomly assigns the participants to the groups or randomly selects samples. The effect of indoor plants is measured by the difference between outcomes of measurements from surveys or measuring devices from experimental and control groups.

The present thesis focuses on the research methodology and experimental setups. Therefore, I organized these papers since 2011 to 2016, as shown in Table 3.3, because many articles were reviewed in the five review papers (mentioned in chapter 1). The organization considers the following: the test space, the country of study, the experimental design, the comparison between two groups, the number of participants and the response rate, the number of potted plants used indoors, the type of measurements, the concerns and objectives of a study, and the findings in the publications.

There are 20 research articles during the specified period. The test spaces used in these investigations are mainly workplaces including offices in buildings, rooms in hospitals, and classrooms in schools and universities. The indoor conditions were considered in few articles (Evensen et al., 2013; Qin et al., 2013; Jumeno and Matsumoto, 2015; Lee et al., 2015; Nejati et al., 2016). The workplaces were air conditioned to the indoor air temperature of 21˚C to 25˚C and relative humidity about 50%, and the lightening was varied and had a range from 400 to 1370 lux. Table 3.3 also shows a wide variety of the studied countries.

In the experimental design, as shown in Table 3.3, the studies have established a variety of research methods. Within-subjects were performed in nine articles, and between-subjects were performed in seven articles. There is one article (Benfield et al., 2013) conducted a quasi-experiment, which is field research with controlled variables for a long period. The comparisons were applied to control and experimental groups, as shown in Table 3.2, which include using plants in new and old buildings, using artificial and real flowers, and visual interaction to a concrete wall and to a plant, plants with and without foliage, and experiments between planting and using digital devices. In the within-subjects design, the comparison is between the pretest and posttest, and grouping into levels of different interior amenities including indoor plants.

For sample sizing used in research, the number of participants has a broad range from 4 to 947 participants with different response rates of a range of 32.8% to 100%. The large sample size more than 100 participants was collected during online surveys through the entire institutions, such as hospitals, office buildings, and campuses, which are sent by institution managers. The participants fill in the surveys more than one with an interval of minimum three months. To evaluate the effect of indoor plants, the scientists should provide a comparison between different survey outcomes. The large sample size may provide external validity of research by achieving generalization as long as achieving the internal validity. However, it consumes time and effort, and many requirements are needed to start the process as well as the massive data to be analyzed. The small sample size, which ranges from 20 to 100, is manageable regardless the low statistical power, which was not calculated for the majority of articles.

The results have shown that many psychological and physiological benefits were observed from using indoor plants. The indoor plants have a potential impact to improve human health, enhance restoration and attention, improve office environment and increase work productivity, decrease stress, and relatively increase the awareness of global warming by observing plants without foliage. In this literature, we classified the significance of results, to quantify the effect of indoor plants, into three levels: relative, significant, and substantial improvement based on the effect size of the results or based what scientists have revealed in their research. Psychological scientists have evaluated the significance of results in according to significant statistical validity (Goodwin, 2002) based on three factors: limiting Type I error to be less than 0.05 or 0.01 ($p<0.05$ or $p<0.01$); limiting Type II error to be less than 0.20 ($\beta<0.20$) resulting in the statistical power more than or equal to 80%; and evaluating the effect size of the indoor plants on behavior.

Accordingly, there are only four articles showed substantial results because of the way the research was conducted: random assignment of participants to control the participant bias (Guéguen, 2012); applying two measurements, subjective and physical, especially for a small sample size (Qin et al., 2013); random selection longitudinal study for two years (Gray and Birrell, 2014); and using analytic combination network (Chen et al., 2014). In addition, the significant improvement has appeared in studies that conducted within-subjects design more than that between-subjects design, as shown in Table 3.3 (a, b and c). Moreover, the relative-improvement results have appeared in a between-subjects design. The reason for that, the studies have focused on the visual experience of plants, and there are no blinded experiments to avoid some confounding variables that affect the participants of both groups, so the difference between-groups outcomes was not clear whether for indoor plants or other factors.

3.4.1 Psychological measurements

The psychological measurements were mostly performed by three main measurements: physiological testing, subjective measurements, and objective measurements.

For physiological testing, several measurements were taken from the participants such as heart rate and heart rate variability by a portable electrocardiograph, four bands of brainwaves (δ-band, θ-band, α-band, β-band) by using electrocardiogram (ECG), skin resistance, respiration rate, fingertip blood flow, blood pressure, and pulse rate data. These devices are attached to the participants' wrist, ankle, fingers, forehead, and other places on the human body. Some studies have used some of the psychological measuring devices in estimating the effect of indoor plants on mood state, heart rate variability, and blood pressure (Jang et al., 2012; and Qin et al., 2014).

For subjective measurements, some surveys were conducting to assess the psychological effects of indoor plants. Each survey can be classified into sections; each has questions or statements to assess the mood of interest in Likert-type scale. For example, the semantic differential (SD) scale is satisfaction survey depending on a self-rating assessment that is used to describe emotional responses, therapeutic influences, and participant preferences as in studies (e.g., Lee et al., 2015; Igarashi et al., 2015).

Table 3.3 a: Research method of the impact of indoor plants on psychological status.

References	Test space	Country	Experimental design	Comparison	No. of participants	No. of plants	Measurements	Concerns	Results
Kim et al. (2011)	Office	Korea	Between-subjects, with treatment and control groups, three measurements	Old and new office	71	47	Q	Human health: Physical and mental health	↑
Raanaas, et al. (2011)	Room	Norway	Between-subjects variable, within-subjects with three measures	w/p, w/o PTPT	34	3	MT	Attention restoration	↑
Smith et al. (2011)	Office	UK	Between-subjects with two levels of planting	w/p, w/o	204, RR=47% 151, RR=34.8%	14, 58	OS	Office environment, human health	↑↑
Gou and Lau (2012)	30 Open-plan offices	Hong Kong	Between-subjects according to plants and partitions	w/p, w/o	469 (155 w/p, 314 wo/p)	NS	Q	Human health, office environment	↑↑
Guéguen (2012)	Room (no window)	France	Randomly assigned to two groups, between-subjects	Plants with and without foliage	60	2	Q	Global worming beliefs	↑↑↑
			Randomly assigned to five groups, between-subjects	w/o, 1-plant with & without foliage, 3-plants with & without foliage	150	1 to 3	Q		↑↑↑

Table 3.3 b: Research method of the impact of indoor plants on psychological status…continued

References	Test space	Country	Experimental design	Comparison	No. of participants	No. of plants	Measure-ments	Concerns	Results
Taib and Abdullah (2012)	21-storey Office building	Malaysia	Simple random sampling	Visiting sky-court, balcony, and rooftop gardens	102, RR=50%	According to the size	IN	Comfort level, landscape preferences	↑
Qin et al. (2013)	Offices	China	within-subject with three levels: colour, odour, size, and two measurements	w/p, w/o	4 to 8	6	Q , PM	Satisfaction, physiological measurements	↑↑↑
Lin et al (2013)	2,245 Hospitals	Taiwan	Within-subjects, according to four factors	Interior amenities, No control group	737, RR=32.8%	411	OS	Work environment	↑↑
Aenchbacher et al. (2013)	School	USA	Within-subjects, pre- and post-measures	PTPT, No control group	16	Biowall	Q	Awareness, engagement	↑↑
Benfield et al. (2013)	University	USA	quasi-experiment, two identical groups	Natural view, concrete wall	567	open grassy area	Q	Student behavior - Grades	↑↑
Evensen et al. (2013)	Computer workstations	Sweden	Between-subjects, mixed randomized, with repeated measures	w/p, w/o	85	4	MT , SE	Attention capacity	↑
Weng and Chiang (2014)	Campus	Taiwan	Between-subjects, five activities and participants choose only one	Indoor and outdoor activities	203 (w/p 48)	NM	Q	Restoration - Stress relief	↑

Table 3.3 c: Research method of intervention of indoor plants in human psychology … continued

References	Test space	Country	Experimental design	Comparison	No. of participants	No. of plants	Measurements	Concerns	Results
Chen et al. (2014)	----	Taiwan	Analytic network process to determine best combination of three control factors and three levels	music, essential oil, plants, No control groups	52 data	7	Q, others	Stress relief	↑↑↑
Jang et al. (2014)	University	Korea	Within-subjects, repeated measures for five levels	Green foliage, colorful flowers	30	5	Q , PM	Brain waves, emotions	↑↑
Nieuwenhuis et al. (2014)	Open-plan office [a]	The Netherlands and U.K.	Between-subjects, and within-subjects repeated measures	w/p, w/o	250, RR=66%	3 per 5 desks	Q	Work environment, concentration, air quality, productivity	↑↑
	Open-plan office [b]	The Netherlands		w/p, w/o	191, RR=75%, 70%	1 per desk	Q		↑
	Open-plan office [b]	The Netherlands		PTPT	33	8 large	MT	productivity	↑↑
Gray and Birrell (2014)	Office building	Australia	Two-year longitudinal study, randomly selected, within-subjects	PTPT	26	Biophilic design	OS, IN	Productivity - Workspace performance	↑↑↑
Mangone et al. (2014)	Open-plan office	The Netherlands	Quasi-experiments, four rooms	w/p, w/o	67, (12-15 each room)	53 plants: tall 2m, small 0.5 m	Q	Thermal comfort	↑↑
Igarashi et al. (2015)	School	Japan	Within-subjects, two levels, two measures	Real and artificial plants	40	1	Q , PM	Visual stimulation	↑↑
Jumeno and Matsumoto (2015)	University	Japan	Within-subjects, repeated measures, four test conditions	PTPT	15	6	Q , MT	Meditation - Attention - Stress relief	↑↑
Lee et al. (2015)	Room	Japan and Korea	Crossover, between-subjects, random assigned, two groups	Transplanting plant, computer task	24	1	Q , SE	Stress relief	↑↑
Nejati et al. (2016)	Hospital	US	Multi-method approach, cross-sectional study	balconies, window views, artwork, or plants	947	NS	IN, Q, SE	Restorative	↑

↑	relative or little improvement	RR	response rate	PTPT	Pre-test and Post-test	PM	Physical Measurement
↑↑	significant improvement	NS	Not Specific	w/p	With plants	IN	Interviews
↑↑↑	substantial improvement	a	Same floor	w/o	Without plants	MT	Mental Tasks
		b	Different floor	Q	Questionnaires and Surveys	OS	Online Survey
				SE	Self-Evaluation		

Also, thermal comfort survey is used to assess thermal satisfaction by providing questions related to the degree of satisfaction of indoor environmental conditions. Most of studies used Occupant Survey of ASHRAE 2010. This survey has a seven-point scale from too cold condition to too hot condition. It can be used in determining the predicted mean votes, and dissatisfied predicted votes (Mangone et al., 2014); Taib and Abdullah, 2012)

Objective measurements are performed by applying metal tests or measuring the productivity performance. Attention restorative theory uses a cognitive approach to explain the benefits of subjecting to a certain object by applying mental tests. Eversen et al. (2015) used the Reading Span Task to measure the directed attention capacity and self-report evaluation assessing the attention level adding ornamental plants to an office. Sentences are presented on a screen, the participant read them loudly and write the last word in each sentence. Similar methodology was used by Raanaas et al. (2011) to evaluate the existence of the indoor plants in an office with and without plants. Both studies showed that the indoor plants have a significant effect on improving attention. Moreover, productivity covers a diversity of activities such as routine work and creativity. Assessing the productivity is by measuring the performance of participants or by recording their perception of their productivity. Nieuwenhuis et al. (2014) used both ways measuring productivity: one way is to record the perception of workers about their productivity in a company before and after adding the indoor plants (which refers to subjective measurements) and measuring the performance of workers by measuring average handling time before and after adding indoor plants (objective measurements). The productivity level was increased after adding ornamental plants in the company. In addition, Dorizas et al. (2015) used different methods to assess students' productivity by measuring attention and concentration tests to evaluate mental performance which include math test and code test and are repeated before and after exposing a student to a subject. Others by assessing the course grades of students and attendances pre- and post-experiments such as in (Benfield et al., 2015)

3.4.2 Research validity

The validity of conducting a psychological research is divided into four major types, which are constructed, statistical conclusion, internal, and external (Stangor, 2010). The construct validity refers to defining the independent and dependent variables meaningfully. The statistical conclusion validity refers to having statistically significant results based on the significance level of 5% or 1% to produce a p-value of less than 0.05 or less than 0.01, respectively, which are defined by the researchers at the beginning of experimental work. The internal validity refers to the extent to which a study is free from methodological flaws, especially confounding variables. Lastly, the external validity refers to the ability to generalize the results beyond the completed experiment.

The internal validity of an experiment can be affected by number of factors including the following: history, which refers to possible events or exposure that affect the posttest scores; maturation, which refers to gaining knowledge or experience of particular objects, and it sometimes leads to habituation and potential expectancy effects as it lacks the interest of the exposure to the object; regression, which pushes the outcome scores close to the extreme one; testing, which refers to pretest scores having a possible effect on posttest scores; and instrumentation, which refers to the change in the measurements from the pretest to the posttest. There are also other factors related to participation including selection effects when the groups are not equivalent. However, it can be solved by assigning or selecting the participants randomly to each group. Also, the attrition, which refers to when some participants do not complete the experiment they begin. It affects other participants to be concerned about the experiment. They may respond to the conducted surveys in a biased way.

There are two experimental designs: the between-subjects design and the within-subjects design. The former is more likely to have such confounding factors which affects the obtained results and sometimes will have a quite differences between the mean values of the control and experimental groups. While the latter, which is the within-subjects design, has resolved these issues by random assignment and establishing a control group to eliminate the confounding variables from pre-post studies. The within-subjects this design has shown the significance of indoor plants in human psychology more than between- subjects design.

The external validity can be achieved by generalizing in one of three ways: population, environment, or time (Goodwin, 2002). The most common type of intervention is generalizing by population. Unfortunately, the previous studies mostly have focused on specific groups such as students in schools or campuses, patients and professionals in hospitals, and workers in companies and offices. They have also collected small and large sample sizes from a certain population.

Overall, several studies have shown the psychological benefits of indoor plants on occupants. These benefits include improving office environment, increasing work productivity, improving human health, increasing concentration and attention, and reducing stress. The experimental design included the between-subjects, within-subjects, and quasi-experiment designs. The within-subject and quasi-experiment designs have shown significant results in the psychological benefits of indoor plants.

General in this chapter, we captured many articles that provided experimental investigations to study the impact of indoor plants in the three categories: indoor air quality (removal and emission), energy use, and psychological benefits. For each category, we organized all the articles captured that are related to this category regarding the studied parameters in laboratory and field studies. The results from field studies did not substantially support the findings of laboratory studies in all categories. we found that the indoor plants have limited impact on indoor air quality, a small impact on energy use, and showed significant psychological effects. In the next chapter, I will discuss and integrate the findings obtained in each category into different scenarios.

Chapter 4 Discussion

The previous chapter presented an analysis of the previous studies that investigated the effect of indoor plants and greenery systems on indoor air quality including possible emissions, energy saving and psychological effects of occupants. This chapter discusses the obtained results in details in the same order and integrate the findings to provide a complete picture of the impacts of plants on indoor environments.

4.1 The impact of indoor plants on indoor air quality

The removal and emission of plants were analyzed in separate sections (Section 3.1 and 3.2). In this section, I followed the same concept since the pollutant removal by indoor plants and their effect on indoor quality is discussed as a first part of the impact similar to previous chapter. The second part is to discuss the emissions from indoor plants and their possible effect on the indoor air quality, which is presented in the following section.

I found that the ability of indoor plants to produce a clean air is limited based on the analysis of 46 articles and calculating CADR values through the articles. To explain more about the CADR values. Figure 3.1 of Chapter 3 is explored in Table 4.1 to show more details about the maximum CADR values calculated based on the information given in the 44 articles. Table 4.1 presents for each article the initial concentration, and the final concentration of a specified contaminant injected into a test chamber, the plant species used for the test, the exposure time, the natural decay rate, the total decay rate, and the maximum CADR values. Table 4.2 shows the initial concentration, final concentration, natural and total decay rates, and the airflow rate through the DBAF system for the last two articles (Wang and Zhang, 2011; Wang et al., 2014).

Some important observations are found from the Table 4.1, such as the ratio of final to initial concentrations (C_t/C_0), which represents the contamination reduction ratio ranging from 0.001 (Mosaddegh et al., 2014) to 0.99 (Kim et al., 2010), and exposure time ranging from about 1.3 h (Tani et al., 2007) to 1152 h (48 days) (Collins et al., 2000). There are 12 articles implementing two investigations (with and without plants). For example, the natural decay rate of toluene in

(James et al., 2008) was -0.0023 h^{-1}, while the total decay rate for the same mixture using a plant species of *Mammalian Cytochrome* P450 2E3 was -0.0409 h^{-1}, which results in low CADR value of 1.54E-06 m^3/h.

However, the removal efficiency was almost 100%. Another example of higher CADR value, (Kim et al., 2010), the formaldehyde concentration reduction ratio (C_t/C_0) by using *Dendropanax morbifera Nakai* was 0.007, the total decay loss was -0.9792 h^{-1}, but the investigation was only conducted on plants, so the natural decay rate is assumed to be zero. Therefore, the CADR value was 0.9755 m^3/h. Although the CADR values for with plants only is higher than that of with and without plants, both of them have lower CADR values less than 1 m^3/h

From Table 4.1c, the toluene concentration reduction ratio (C_t/C_0) by using DBAF system was 0.046, and the exposure time is 0.22 h, which results in the total decay rate to be -13.90 h^{-1}. This system used contaminated airflow rate of 930 m^3/h. Therefore, the CADR value calculated by the authors was 756.7 m^3/h (Wang and Zhang, 2011). Similarly, the formaldehyde concentration ratio (C_t/C_0) by using the same system was 0.092 in a test chamber during the exposure time of 0.75 h. The total and natural decay rate were -0.0022 and -3.1861 h, respectively. Therefore, the CADR value was 16.35 m^3/h (Wang et al., 2014).

To understand how the CADR value varies with respect to the concentration reduction ratio, we have to deal with basic governing equation (2.1) under restricted assumptions. For ideal conditions, we assume that there is no loss from the test chamber, the air is well-mixed, and negligible infiltration rate and deposition rates. The CADR value is equal to the volume of the test chamber multiplied by the difference of the total and natural decay rates (CADR = V_c ($K_t - K_n$)). The decay rate, K, is defined as the rate at which the contaminant concentration decays over time, which is represented as an exponential decrease. That means, the decay rate depends on the ratio of the final to initial concentration of the contaminant injected into the chamber expressed as $A = C_t/C_0$ and the exposure time, t, as shown in equation 4.1.

$$K = -\frac{\ln\left(\frac{C_t}{C_0}\right)}{t} = -\frac{\ln(A)}{t} \tag{4.1}$$

Table 4.1 a: The decay loss for maximum CADR values across plant species studied in articles

No.	References	Contaminants	Plant Species	C_0 with plants	C_t with plants	t (h)	K_t (h^{-1})	K_n (h^{-1})	CADR (m^3/h)
1	Chun et al., 2010	mixture of (benzene, toluene, m,p-xylene, o-xylene)	*Dieffenbachia*	2.085 μL/L	0.0001 μL/L	12	-0.1658	0	0.00014
2	James et al., 2008	toluene	*Mammalian Cytochrome* P450 2E3	10.5 μg	0.5 μg	72	-0.0409	-0.0023	1.54E-06 *
3	Saiyood et al., 2010	Bisphenol A [BPA, 2,2-bis(4-hydroxyphenyl) propane]	*Dracaena sanderiana* and *D. fragrans*	20 μmole	5.16 μmole	480	-0.0037	0	2.92E-06
4	Yang et al., 2009	TCE (Trichloroethylene)	*Fittonia argyroneura*	44.3 mg/m^3	19.95 mg/m^3	6	-0.1330	0	0.0503
5	Baosheng et al., 2009	formaldehyde	phoenix roebelenii	8 ppm	6.278 ppm	5	-0.2404	0	0.0705 *
6	Hasegawa et al., 2002	formaldehyde	Schefflera arboricola	50 ppm	45 ppm	12	-0.0088	0	0.0020
7	Hasegawa et al., 2004	formaldehyde	N. exaltata	65 ppm	47.45 ppm	4	-0.0774	-0.0027	0.0172 *
8	Oyabu et al., 2001	formaldehyde	*Epipremnum aureum*	50 ppm	24.25 ppm	70	-0.0105	0	0.0031
9	Oyabu et al., 2003	ammonia	*Ficus elastica*	5 ppm	2.828 ppm	5	-0.1140	0	0.0342
10	Oyabu et al., 2003	gasoline	*Epipremnum aureum*	0.05 ml	0.0211 ml	140	-0.0062	-0.0014	0.0014 *
11	Sawada et al., 2003	formaldehyde	*Pelargonium X hortorum*	8 ppm	5.913 ppm	12	-0.0252	0	0.0076
12	Sawada et al., 2007	xylene	transgenic tobacco	1.5 ppm	1.164 ppm	12	-0.0212	0	0.0063
13	Aydogan and Montoya, 2011	formaldehyde	*Hedera helix*	2000 μg/m^3	241 μg/m^3	25	-0.5871	0	0.044
14	Collins et al., 2000	benzene	*Rubud fruticosus*	1 mg/m^3	3.4 μg/m^3	1152	-0.0049	0	0.0012
15	Cruz et al., 2014	toluene	*Hedera helix*	0.35 mg/m^3	0.127 mg/m^3	48	-0.0212	0	0.0012
16	De Kempeneer et al., 2004	toluene	*Azalea indica*	100 ppmv	2 ppmv	100	-0.0374	-0.0016	0.0008 *
17	Godish and Guindon, 1989	formaldehyde	*Chlorophyturn elatum*	0.52 ppm	0.04 ppm	192	-0.0134	0	0.0039
18	Jin et al., 2013	formaldehyde	*Melissa officinalis*	2.5 mg/m^3	0.113 mg/m^3	5	-0.6187	0	0.2339
19	Khoa et al., 2013	formaldehyde	*Lindsaea javanensis Bl.*	13 mg/m^3	1.794 mg/m^3	24	-0.0825	0	0.0297
20	Kim et al., 2011	toluene	*Schefflera elegantissima*	4.896 mg/m^3	0.391 mg/m^3	18	-0.1404	0	0.0018

Table 4.1 b: The decay loss for maximum CADR values across plant species studied in articles

No.	References	Contaminants	Plant Species	C_0 with plants	C_t with plants	t (h)	K_t (h^{-1})	K_n (h^{-1})	CADR (m^3/h)
21	Kim et al., 2010	formaldehyde	*Dendropanax morbifera Nakai*	2.454 mg/m^3	2.436 mg/m^3	5	-0.9792	0	0.9755
22	Kim et al., 2009	formaldehyde	*Epipremnum aureum*	2.454 mg/m^3	1.1145 mg/m^3	5	-0.1579	0	0.1573
23	Kim et al., 2008	formaldehyde	*Ficus benjamina*	2.454 mg/m^3	1.7 mg/m^3	5	-0.0734	0	0.0731
24	Kim and Kim, 2008	formaldehyde	Spathiphyllum	2.454 mg/m^3	0.406 mg/m^3	5	-0.4576	0	0.4559
25	Kim and Lee, 2008	formaldehyde	*Phalaenopsis*	2.454 mg/m^3	0.405 mg/m^3	5	-0.9009	0	0.8976
26	Kim et al., 2012	toluene	*Begonia maculata Raddi*	4.896 mg/m^3	4.447 mg/m^3	12	-0.0080	0	1.76E-05
27	Liu et al., 2007	benzene	*Crassula portulacea*	0.5 mg/m^3	0.085 mg/m^3	16	-0.1106	0	0.0083
28	Mosaddegh et al., 2014	benzene	*Opuntia microdasys*	3.19 mg/m^3	0.0032 mg/m^3	120	-0.0693	-0.0073	0.0031 *
29	Newkirk et al., 2014	toluene	a biowall	200 ppm	140 ppm	3.8	-0.1200	-0.0429	0.0056 *
30	Orwell et al., 2004	Benzene	*Epipremnum aureum*	25 ppm	5 ppm	48	-0.0335	0	0.0072
31	Porter, 1994	toluene	*Dieffenbachia amoena*	8669 μg/m^3	5785.7 μg/m^3	3	-0.1349	0	0.1348
32	Sriprapat and Thiravetyan, 2013	toluene	*Zamioculcas zamiifolia*	12.5 μmole	0.125 μmole	120	-0.0709	-0.0011	0.0011 *
33	Tani and Hewitt, 2009	propionaldehyde	*Spathiphyllum clevelandii*	34 ppbv	25 ppbv	1.67	-0.1845	-0.0706	0.0034 *
34	Tani et al., 2007	Methyl isobutyl ketone	*Epipremnum aureum*	75 ppbv	64 ppbv	1.33	-0.1190	-0.0253	0.0028 *
35	Torpy et al., 2013	benzene	*Spathiphyllum ‘Petite’*	25 ppmv	6 ppmv	144	-0.0099	0	0.0021
36	Treesubsuntorn and Tiravetyan, 2012	Benzene	*Dracaena sanderiana*	20 ppm	6.3 ppm	72	-0.0163	0	0.0020
37	Wolverton and Wolverton, 1993	formaldehyde	*Nephrolepis exaltata*	3.5 ppm	0.4 ppm	12	-0.1808	0	0.0560
38	Wolverton et al., 1989	beneze	*Hedera helix*	0.235 ppm	0.024 ppm	24	-0.0951	0	0.0417
39	Xu et al., 2011	formaldehyde	*Chlorophytum comosum*	11 mg/m^3	10.45 mg/m^3	72	-0.0007	0	5.37E-05
40	Xu et al., 2013	Toluene	biofilter with microorganisms	0.5 g/m^3	0.4 g/m^3	72	-0.0031	0	1.70E-05
41	Lim et al., 2009	formaldehyde	*Fatsia japonica*	2400 μg/m^3	1708 μg/m^3	5	-0.0684	-0.0076	0.0608 *
42	Yoo et al., 2006	mixture of benzene and toluene	*Spathip**hyll**um wallisii*	3.48 mg/m^3	1.023 mg/m^3	6	-0.2040	0	0.0586
43	Wood et al., 2002	benzene	*Howea forsteriana*	25 ppm	7 ppm	48	-0.0057	-0.0038	0.0019 *
44	Wood et al., 2006	toluene	*Dracaena deremensis*	0.572 ppm	0.004 ppm	24	-0.3100	0	0.0670

Table 4.1 c: The decay loss for high CADR values.

No.	References	Contaminants	Plant Species	C_0 with plants	C_t with plants	t (h)	Q_f (m^3/h)	K_t (h^{-1})	K_n (h^{-1})	CADR (m^3/h)
45	Wang and Zhang, 2011	toluene	DBAF system with *Epipremnum aureum*	2.16 ppm	0.1 ppm	0.22	930	-13.90	0	756.7
46	Wang et al., 2014	formaldehyde	DBAF system with *Epipremnum aureum*	120 ppb	11 ppb	0.75	20	-3.1861	-0.0022	16.35 *

Since the CADR depends on the decay rate, we need to understand the behaviour of this rate. The variation of the decay loss is graphically represented in Figure 4.1 with respect to different values of exposure time and different concentration reduction ratio, A. The removal efficiency is also illustrated in Figure 4.1, which is expressed as $\eta = (C_0\text{-}C_t)/C_0 \ = 1 - A$, which is a decreasing linear relationship with respect to A. As shown in the figure, the decay loss decreases by increasing the concentration reduction ratio A and also decreases by increasing the exposure time. For example, concentration reduction ratio A of 0.2, the decay rate, K, at time t = 5 min is about 19 h^{-1}, and the decay rate at time t = 1 h is 1.6 h^{-1}. That means the decay rate is increased by the order of magnitude of 1 when the time is decreased by the order of magnitude of 1.

Most of the articles, the exposure time is in hours and days. Taking an example of (Mosaddegh et al., 2014), the lowest concentration reduction ratio was A = 0.001, which has the highest removal efficiency of 100%, and the exposure time was 120 h. The decay loss, K, will be 0.06h^{-1} according to Figure 4.1, which reflects on the small CADR value.

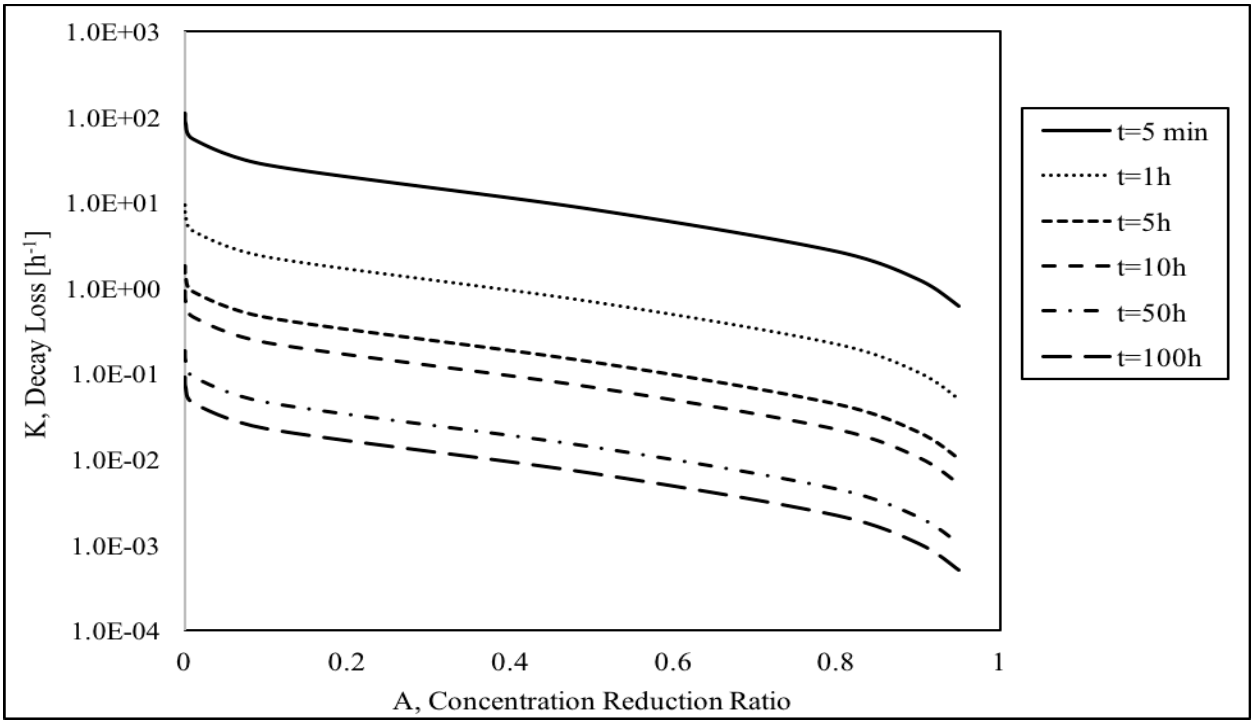

Figure 4.1: The variation of decay loss (K) with respect to the concentration ratio (A) and the exposure time (t)

The effectiveness is to measure the extent of the impact of using indoor plants in a real room or office. In other words, the effectiveness shows the impact of using plants over no-plant case in a real location. The proposed scenario is a typical office of an air-tight structure with a volume of 75 m^3. The office has a well-mixed air, and ventilation rate of 0.36 h^{-1} based on (ASHRAE, 2013), and the penetration rate and deposition rate are assumed to be neglected just for the sake of simplicity, as shown in Equation 4.2. Therefore, the effectiveness depends on the CADR value, office volume, and exchange rate. It will be maximized since other factors are neglected. According to Table 4.1, the maximum effectiveness, according to the current scenario, obtained was 3.5% for the CADR value of 0.9755 m^3/h (Kim et al., 2010). This value will be reduced by taking the account of other factors (e.g., the deposition rate and penetration rate).

$$H = 1 - \frac{\lambda}{\lambda + \frac{CADR}{V}} \tag{4.2}$$

$$H = 1 - \frac{\lambda + \beta}{\lambda + \beta + \frac{CADR}{V}} \tag{4.3}$$

$$CADR = V(\lambda + \beta)\left(\frac{1}{1 - H}\text{-}1\right) \tag{4.4}$$

For any air cleaners, the effectiveness should be about 80% to show their impact in real life according to the AHAM performance recommendation (Shaughnessy and Sextro, 2006). Equation 4.3 illustrates the effectiveness (H) in terms of ventilation rate (λ), deposition rate (β**)** and CADR value. To have an effectiveness of 80%, for the same office (75 m^3) with a ventilation rate of $\lambda = 0.36$ h^{-1} and no deposition rate ($\beta = 0$). The CADR value will be 108 m^3/h according to equation (4.4). Under the same previous conditions but taking an account of deposition rate equals to the ventilation rate ($\beta = 0.36$ h^{-1}). The CADR value will be doubled (216 m^3/h). To evaluate the quantity of a potted plant needed to have high CADR value, Kim et al. (2010) used one potted plant of *Dendropanax morbifera Nakai* with leaf area of 0.35 m^2 to remove formaldehyde from the test chamber, which produced a CADR value of 0.9755 m^3/h (~1 m^3/h). To have an effectiveness of 80% in the typical office and CADR value of 216 m^3/h, the office will need almost 216 potted plants of the same kind. This is an unrealistic situation to fill more than half of the office with plants in order to have effective pollutant removal.

The formulas do not have any uncertainty. However, there are uncertainties involved in the following: the satisfaction of the assumptions provided with each formula, the definition of CADR, and the uncertainty of any measurements. If any of these assumptions are not satisfied (i.e., the air inside the chamber is not well-mixed, there are deposition rate and other emission sources inside the chamber, there is leakage from the chamber), the value for each (CADR and H) will be reduced from the ideal situation. The CADR value is estimated by the difference between the natural and total decay rates. Only 11 articles provided two measurements with and without plants to evaluate the effect of plant existence in pollutant removal. The ratio of natural to total decay rates ranged (k_n/k_t) from 0.016 (Sriprapat and Thiravetyan, 2013) to 0.383 (Tani and Hewitt, 2009), which yields to CADR values of 0.0011 and 0.0034 m^3/h, respectively. That means, the other CADR values have increased by 2 to 38% for those were calculated by total decay rates only not by the difference between the total and natural decay rates. Another factor that significantly impacts the uncertainty is the accuracy of devices such as gas chromatography for measuring the concentration and leaf index measurements, which provide uncertainty of 50% of leaf area index. Leaf index area is implemented in calculating the final concentration in the test chamber since the final concentration is calculated as the product of the removal rate per leaf area and the leaf index area. Both uncertainty in leaf area index and concentration measurements yields to uncertainty in the final concentration. Any uncertainty in CADR value will consequently affect the effectiveness value in addition to satisfying the assumptions (i.e., the ventilation rate and deposition rate). Despite the uncertainty, the values of CADR and H for ideal cases are maximized and having extremely low values, which show the limited potential effect of indoor plants on indoor air quality.

In conclusion, despite the indoor plants have been experimentally tested on pollutant removal, they were able to reduce the contamination in a test chambers but under long time exposure in hours and days. The combination of reduction ratio and time yields to the formula of decay rates. The experimental test showed that the total and natural decay rates are very small resulting in small CADR values. That shows the limited impact of indoor plants on the indoor air quality.

4.2 The impact of emission rates of indoor plants on occupants

Plant emissions are of great importance to its growth and survival since they have distinct biological roles in the attraction of pollinators, protection against pathogens (Dudareva et al., 2004), and provision of scent and flavour (Goff and Klee, 2006). However, few studies have related these emissions with indoor air quality. I found that the VOCs and microorganism are major emissions from plants. The major VOCs groups from indoor plants are a group of terpenoids, which can react with ozone outdoors and possibly indoors producing harmful byproducts. In addition, some microorganism communities can act as opportunist pathogens. A comparison is also established between interior plants and other indoor sources that emit similar emission groups to measure the effect of plant emissions on indoor air quality. The comparison is classified according to the type of emissions mentioned in section 3.2; the VOC emissions, especially terpenoids group, and microorganisms.

Ozone can enter the indoor environment from outdoors through ventilation air (Weschler, 2006). The indoor to outdoor ozone ratio varies from 10 to 80% in hospitals, offices, homes, and school in North America (Weschler, 2000). Also, ozone can be introduced by indoor sources such as printers, photocopiers, and ion generator air cleaners (Niu et al., 2001, Kagi et al., 2007; Zhang et al., 2011; Siegel, 2016). For example, three consumer products were investigated in a test chamber. They were oil-based degreaser, a general-purpose surface cleaner, and an air freshener (Singer et al., 2006). They contain terpenes, ozone reactive chemicals, and the steady state concentration ranged between 1 and 10 ppb. Comparing the amount of terpenoids compounds from both ornamental plants and other consumer products is a possible way to assess their effect on indoor air quality and ozone formation. Both *d*-limonene and linalool were found from air fresher studied in (Singer et al., 2006) and some of four ornamental plants studied in (Yang et al., 2009). Plants emit much less VOCs than air fresheners since the VOC emission rate from the ornamental plants are lower that the VOC emission rates by 3-5 order of magnitude by comparing the findings of (Singer et al., 2006) and (Yang et al., 2009).

Fungi are ubiquitous outdoors and indoors and live in every part of the biosphere, in humans, animals, plants, soil, oceans and air. Because of their abundance, it is challenging to verify identify the indoor source of microorganisms. Human activities, pets, and water-damaged houses are among the predominant indoor sources of microorganisms. It was not clear that indoor plants may affect the microbial loads since adding plants into office did not make a significant change in indoor microorganisms compared to offices with plants as investigated by (Torpy et al., 2013). Many reasons can be involved as the following: the office buildings did not experience any mould issues, the buildings were air tight and equipped with HVAC systems, and the microbial sampling was taken before agitating and maintenance (watering and trimming all dead leaves). These factors help controlling the increase in fungal spore concentration. Also, the major source of microorganisms was probably from the outdoors through the HVAC systems, since the total counts of fungal spore loads of outdoors were an order of magnitude higher than that of indoors, and the outdoor samples had the most dominant fungal genera (Cladosporium, Acremonium and Alternaria) similar to that of indoors.

There are many other factors can be associated with indoor plants and affect the microbial loads. Such factors are watering systems, the type of the soil, the relative humidity, and other agitation factors. These factors are covered below in separate paragraphs.

First, watering systems can include self-watering, manual watering, spray watering, and overhead watering systems. Most of the mentioned studies have taken air samples before irrigation process and maintenance. The air sampler was located close to the floor and to the plant benches. The type of watering may be associated with the increase of the microbial load despite the environmental variation between the studies. For example, self-watering pots showed less indoor airborne spore counts as in office buildings (48-126 cfu/m^3) (Torpy et al., 2013). The airborne fungal spores were slightly higher (10^3-10^4 cfu/m^3) using watering close to the soil without wetting the plant leaves and in homes with houseplants and greenhouses (Burge et al., 1982). However, using a weekly spray watering with a garden hose over cactus plants, the fungal spore counts reached >10^4 cfu/m^3 (Burge et al., 1982). Also, the fungal spore loads greenhouses using overhead watering systems (10^4 spores/m^3) was higher than the manually watering systems (5×10^3 spores/m^3) according to (Li and La Mondia, 2010).

Second, the type of the soil also affects the airborne fungal spores. A greenhouse containing potted plants recently filled with clean pebbles had less fungal spore by an order of magnitude than that filled with old cinders (red sand) before and during watering (Burge et al., 1982). Therefore, filling the soil of cactus plants with clean pebbles instead of cinder reduced the amount of the fungal spores, but still higher that other greenhouses because of the spray watering systems used, which may be associated with fungal propagation (Burge et al., 1982).

Third, the amount of indoor plants may affect the relative humidity as well as the airborne fungal spore loads. In an investigation of office buildings, the offices had two to three ornamental plants (Torpy et al., 2013), which was probably associated with a slight increase in the relative humidity by 1.3% ranging from 40.2 to 69.3% over seasonal variations. The range of the fungal spore load was 48 to 126 cfu/m^3. In addition, in homes with more than ten houseplants and greenhouses, the relative humidity reached greater than 70%, and the fungal spore loads ranged from 10^3 to 10^5 cfu/m^3 across the studies of (Burge et al., 1982; Li and LaMondia, 2010). However, in sunny room filled with plants in (Wolverton and Wolerton, 1996), the relative humidity was greater than 70% (75% in summer and 72% in winter) and increased by about 20% over the rooms without plants, but the concentration of fungal and bacterial loads for the sunny room were lower than that of other rooms without plants. There are many reasons may be involved in this particular study; the different hygiene levels among the rooms, the dampness (about 62% and 22.5°C through the seasons) and coldness of other rooms, and the sunny room was not regularly used by occupants. This shows that not only the relative humidity but also other environmental factors should be included to understand the environmental factors influencing the increase in microbial loads indoors.

Finally, other agitation factors, such as forced air movement, are also potentially important. Burge et al. (1982) put a fan in front of the plants and collected air samples to measure the airborne fungal spores, they found that the forced air movement had increased the total fungal spore loads since they help in dispersing fungal spores in the air, but lower that during watering. In addition, using an exhaust fan in greenhouses helps to create negative air pressure, in which reducing the counts of fungal spores indoors (Li and LaMondia, 2010). That is because some fungal genera, including *Aspergillus/Penicillium* and *Cladosporium*, were positively correlated with temperature, relative humidity, and solar radiation and negatively correlated with air pressure and wind speed (Li and LaMondia, 2010), these results are incompatible with the results of (Wolverton and Wolerton, 1996) for the sunny room. Therefore, human activities with plants, such as potting, watering, maintenance, heating and ventilation, are important factors to needed be studied in future to estimate potential human exposure to direct airborne fungal spores from plants.

Comparing the microorganisms from plants with other indoor sources. The fungal and bacterial emission rates for one person may be estimated to be 3.7×10^7 and 7.3×10^6, respectively (Qian et al., 2012; Prussin and Marr, 2015). Fungal spore concentrations vary according to human activates, such as changing mattress sheets (1500 cfu/m^3), and during sweeping the floor (300 cfu/m^3) (Lehtonen et al., 1993). In addition, accommodating a pet can produce up to fungal spore concentration of (1000 cfu/m^3) (Lehtonen et al., 1993; Barberan et al., 2015). Moreover, water-damaged houses can produce a total fungal concentration of 2.55×10^5 cfu/g of dust with doubled level of fungal taxa of Aspergillus and Penicillium and are associated with adverse respiratory effects (Dales et al., 1991; Jaakkola et al., 1992). All of these sources are much greater than that of having potted plants in residences.

The indoor plants contribute substantially to the microbial abundance and diversity in the built environment. Some studies have captured a variety of fungal genera, but not all of them. Total identified fungal genera were 25 genera (Burge et al., 1982), 28 genera (Torpy et al. 2013), and 44 fungal taxa (Li and LaMondia, 2010). In addition, Mahnert et al. (2015) investigated the microbial load after introducing an ornamental plant into a built environment. They isolated a spider plant in a chamber inside the built environment for six months, then removed the chamber. They found a significant increase of enumeration of bacteria, fungi and archaea on the surface of walls and floor with a large variety.

Moreover, other studies than captured in the thesis have shown that the microbial diversity is important to human health. Children who grow up on farms are less likely to have atopic diseases and allergic sensitization than non-farm children who grow up in an urban area (von Mutius & Vercelli, 2010; Vuitton & Dalphin, 2017). Also, the loss of rural area and farms has been correlated with the prevalence of asthma, hay fever, atopic dermatitis and allergic sensitization in an urban area (Riedler et al., 2000). Farming activities include planting, watering, seeding and dealing with soil, livestock raising, consuming their products. Exposure to farming activities by inhalation or ingestion from early or prenatal life provides protective environmental exposures. This exposure may produce a robust and long-lasting innate immunity system for farm children (Ege et al., 2006; von Mutius and Vercelli, 2010). Moreover, the farm exposure is protective to certain allergen and immunoglobulin isotypes (Naleway, 2004; May et al., 2012). That means the microbial diversity of indoor plants plays can enhance the occupant health.

Not all the microorganisms can be identified. For example, Mallany et al. (2000) were interested in *Legionella pneumophillia* in watering plants, but it was not detectable. Also, the bacterial community was not identified in genera and species (Wolverton and Wolverton, 1996) In addition, the fungal genera have been identified in most of the studies rather than bacterial communities. The reason of such identification depends on monitoring of microorganism through sampling and culturing. Air sampling devices separate bioaerosol particles from the air stream and collect them in a medium. Sampling techniques involve impaction used by (Burge et al., 1982; Mallany et al., 2000; Torpy et al., 2013), filtration used by (Li and LaMondia, 2010), impingement and sedimentation used by (Wolverton and Wolverton, 1996) (Jensen and Schafer, 1998 ; Napoli et al., 2012). Culturing microorganisms use culturable media according to the microorganism of interest. The recommended broad spectrum media are malt extract agar and Rose Bengal agar for fungi and tryptic soy agar, casein soy agar and nutrient agar for bacteria. Special selective media are often used to select for the specific microorganism of interest. In addition, some chemicals may be added to the media to restrict the growth of selected fungi and bacteria. Moreover, different incubation times or temperatures can be used to get differential growth on the same medium to identify different genera. Also, a differential media may be used to distinguish among species. Culturable microorganisms can be identified by classical microbiology which includes growth characteristics, colonial morphology, appearance on medium, and pigmentation. They also can be identified by incubation under different clinical end environmental conditions. For nonculturable or nonviable microorganisms, enumeration of suspensions of microorganisms can be identified by using microscopic techniques, endotoxin assay, and diagnostic assays by utilizing nucleic acid or DNA probes. Overall, all microorganisms cannot be identified using one technique.

Overall, few studies have investigated the emission from indoor plants. Emissions from indoor plants are in negligible amount compared to other indoor emissions based on a number of indoor plants. The VOCs from plants are beneficial to plant survival and quality attitude. The terpenoids from plants can react with ozone and produce harmful byproducts but in very limited amounts that are not comparable with emissions. Several studies have focused more on fungal spore load than bacterial loads showing the microbial diversity of indoor plants, which might have a beneficial effect on human health regardless of another harmful species. Loads of microorganisms from indoor plants are much less than other indoor sources. Other factors can stimulate the amount of emissions plants such as irritation, agitation, and environmental factors.

4.3 The impact of plants on energy consumption

The thesis captured most articles from 2010 to 2016 and presented a detailed analysis of the given information and the obtained results from these articles in Section 3.3. I found that the greenery systems can reduce external surface temperature as well as the heat transfer from the walls and roofs. The reduction values change according to many independent variables, such as the greenery classifications, the insulation effect, the climate effect, the reduction mechanisms, and other effective parameters such as solar radiation with respect to the diurnal, seasonal and special variation, the leaf area index, and the moisture content. The different findings from laboratory and field studies are also discussed. In addition, the life cycle analysis is considered for each system in order to evaluate the sustainability. Moreover, we presented alternative methods in order to save more energy consumptions. All of these were discussed below in separate items.

4.3.1 The greenery systems classifications

The greenery systems, as we mentioned before, can be classified into three main systems: green roofs, green façade, and living walls system. Each system has a different construction (Manso and Castro-Gomes, 2015; Safikhani et al., 2014). For example, the green roof can be constructed in layers above each other adding to the roof with this order: a drainage layer, a substrate layer, and a vegetation layer. The green façade systems can be constructed of a substrate layer on the ground, a vegetation layer of self-clinging climbers attached to the wall structure, or supported on wiring system away from the wall structure. The living wall system can also be constructed of geotextile felts, or substrate layers in panels, both are vertically supported on the wall structure and a vegetation layer. A layer of air space may be added between the external wall surface and the vertical greenery systems. Each layer will add a thermal resistance, if the layer has poor thermal conductivity, resulting in relatively decreasing the overall thermal conductivity of a bare wall or a bare roof. The thermal conductivity of vegetated building envelopes can be higher than the insulated walls or roofs in winter seasons. This is because of the stored amount of moisture content that added by precipitation and evapotranspiration processes of plants in the substrate and not able to be evaporated, which adds more heating load to warm the walls and roofs in winter seasons.

4.3.2 The insulation effect

The construction of the greenery systems provides different insulation effects. In a comparison between two green roofing system (Coma et al., 2016), a reference roof is constructed with thermal conductivity of 0.71 W/m^2.K including a gravel of a thermal conductance of 1.21 W/m.K. The other two green roof systems same vegetation and same substrate layers but different drainage layer (rubber crumbs and pozzolana with thermal conductance of 0.13 and 0.55 W/m.K, respectively). Consequently, the thermal conductivity of green-rubber roof and green-pozzolana roof were an average of 0.9 and 1.3 W/m^2.K was more than the reference roof due to the moisture content of the substrate. The green-rubber roof provided better thermal protection against high solar radiation (about 1000 W/m^2) in summer and by 16%. However, in winter, the green roofs consumed more energy by 4% for rubber and 10% for pozzolana compared to the reference roof. That is because of the high relative humidity and precipitation of the temperate climate in Puigverd de Lleida, Spain, which does not allow moisture to evaporate from the substrates, which leads to increasing the thermal conductivity as well as increasing the heating loads. A similar study was performed by (Niachou et al., 2001) to investigate green roofs with and without insulation. They found that the green roof was positively effective with no insulation and reduced energy consumption of a building by 48% compared to green roofs with a moderate and well insulated by 7% and 2%, respectively. This is because the reductions of overall themal conductivities were about 18% and 2% for medorate and well insulated roofs after adding green roofs, respectivley. Also, both of these structures, moderate and well insulated green roofs, had similar external surface temperatures compared that without green roofs.

Many green façade systems are climbing vegetation on the exterior wall of a building. That means adding the thermal conductivity of the vegetated layer to the wall structure, which varies according to the variation of leaf index, which varies seasonally. Susorova et al. (2013) investigated the thermal behaviour of a green façade including conduction, convection and radaition heat transfer and neglecting the moisture transfer, and they found that the thermal resistance of green façade varied between 0 m^2.K/W for no solar radiation to 0.67 m^2.K/W with 600 W/m^2 solar radiation, while the brick wall without vegetation is 0.40 m^2.K/W. Despite the limited information about the thermal resistance or conductivity of the green façade, a plant layer with dense foliage significantly reduced the external temperature as well as the heat transfer through the wall structure (Bolton et al., 2014).

Regarding to living walls, the living wall consists of three layers exterior to the wall structure: felt or substrate, supporting system, and vegetation. In the study of Olivieri et al., (2014), the thermal conductivity of a substrate varies according to the moisture content (dry substrate and damp substrate have a thermal conductance of 0.092 W/m.K and 0.191 W/m.K, respectively. The thermal resistance of a bare wall with dry substrate was 3.051 m^2.K/W, while thermal resistance of a living wall with a wet substrate was 2.691 m^2.K/W, and both of the wall structures were insulated with extruded polystyrene of thermal resistance of 2 m^2.K/W. This experiment showed that with almost equal thermal conductivity (0.33 and 0.37 W/m^2.K for bare wall and living wall, respectively), the living wall was able to reduce the external temperature by 25˚C and internal wall surface by an average of 6.4˚C compared with a bare wall. Overall, every layer adds a thermal resistance to the wall structure resulting in the reduction of the heat transfer of the building structure.

4.3.3 The climate effect

Energy savings associated with plants have been investigated in many locations (see Table 3.2). All the greenery systems have reduced the external temperature of the investigated bare walls resulting in heat transfer reductions during summer seasons and slight to negligible reduction in winter seasons. Most of the greenery systems have been studies in different climates. The green roof systems have been explored in temperate, continental, tropical and dry climates. A comparison was established by (Ascione et al., 2013) to investigate the green roof system in different climates in Spain, Italy, Netherlands, UK, and Norway. It was found that the green roofs can save the energy consumption up from -1% to 5% in winter and 2% to 11% in summer. Also, Coma et al. (2016) investigated the green roof in temperature climates in Spain. They found that the energy saving reached to 2-19% through the year. Alexandri and Juones (2008) investigates the green roofs and living walls in different locations with climate variation (temperate, subarctic, continental, Mediterranea, Steppe, Arid, Rainforest, and Savana climates). Green walls have a stronger effect than green roofs inside the canyon. Nonetheless, The green roofs can decrease the roof temperature by 12.8°C in a summer season. The green façade system was also investigated in temperate and continental climate conditions. The energy saving was reached to 6% to 11% in the cooling season (Feng and Hewage, 2014) and an average of 6% in the heating season (Coma et al., 2014) in temperate climates. Also, there was a heat transfer reduction reaching to 43% in summer by using green façade on a bare wall in continental climates (Susorova et al., 2013). Meanwhile, the living wall systems have been studied in temperate and dry, desert climates. They can save energy by 15% in temperate climates (Pulselli et al., 2014) and reduce heat reduction in summer by an average of 80% (Mazzali et al., 2013), while they can save more energy by 20.5% in dry climates (Haggag et al., 2014). When the climate is getting hotter and drier, the effect of greenery systems becomes greater on building envelopes.

4.3.4 The reduction mechanisms

The variation between the reduction values depends on the energy balance of the greenery systems and the plant characteristics in addition to the latent heat from the moisture content. First, the energy balance of any building envelope consists of three modes of heat transfer: radiation, convection, and conduction. When the vegetated layer is added, it receives short wave radiation from the sun, and it also exchanges longwave thermal radiation between the ground, sky, and surrounding surfaces. Some of the incident radiation is absorbed by the vegetation and transferred by convection, if there is a layer of air, or transferred by conduction to the substrate layer then the bare wall. The energy balance of the vegetated wall also includes an additional term for the radiation exchange between leaves of the plant layer and the substrate surface for the living wall and green roof or the wall surface for the green façade.

Second, for the plant characteristics, there are many parameters affecting the reduction of heat transfer through the wall or roof structure. These parameters include leaf absorptivity, which is the fraction of incident solar radiation absorbed by a leaf (Campbell and Norman, 2012), leaf dimensions, which affect vapor conductance and convective heat between plant leaves, leaf area index which is defined as the total projected area of leaves per unit surface area. The parameters also include the radiation attenuation coefficient, which indicates the decrease in the absorbed radiation in the plant canopy. Besides, they include the leaf stomatal conductance, which is the rate of water vapor leaving the plant surfaces through the pores on the leaf surface during the transpiration.

Third, the latent heat is transferred through the moisture content, which comes from the amount of precipitation, according to the climate variation, the evapotranspiration process of the plants, and the water content in the substrate layer.

4.3.5 The most effective parameters

Among all of these parameters, previous studies have focused on the incident solar radiation, the conduction heat transfer through the wall with and without plants, the leaf index and the moisture content of the greenery systems.

4.3.5.1 Solar radiation

The effect of incident solar radiation on the greenery systems has been diurnal, seasonally, and spatially studied. They have been discussed below.

a. Seasonal variation

A green roof was studied under various locations with different climates (Ascione et al., 2013). The cooling demand of a traditional roof in Tenerife, Spain of semi-arid climates is higher than Sevilla and Rome of temperate climates, and Amsterdam and Oslo of continental climates. Therefore adding a grass lawn on the roof with a drainage and substrate layer reduced the cooling demand by 7% in Tenerife, which was relatively higher than other climates with a range of 3% to 6%. While the heating load was required more in continental climate than temperate climates, and almost negligible in an arid climate. The green roof achieved a higher reduction in heating load in Sevilla which has a subtropical climate by 29% compared to others, which have a range of 6% to 16%. In addition, a green façade was conducted on a laboratory study under various incident solar radiation in the summer season (Susorova et al., 2013), when the solar radiation was zero at night and reached a maximum value of 800 W/m^2 during the day, the reduction in external surface temperature ranged from 0°C to 13.9°C and the corresponding reduction of heat transfer ranged from 0 W/m^2 to 35 W/m^2. Moreover, the living wall was installed on the wall structure in modules by laying the turf on the substrate as studied in (Cheng et al., 2010) in Hongkong of humid subtropical climate. The results showed that the incident solar radiation was between 60 to 290 W/m^2 in the summer. The external surface temperature of using living wall reduced by 10°C during the peak hour. The substrate surface temperature was lower than the external surface temperature of a bare wall by 12°C. Meanwhile, the heat flux of the living wall was an average of 7 W/m^2 compared to an average of 35 W/m^2 the bare wall. That indicates that the higher incident solar radiation the is higher the external temperature reduction and wall heat flux reduction.

b. During the extreme cold weather

Some studies have conducted experimental work on the greenery systems during the extreme cold weather. For example, Bolton et al. (2014) used ivy as a green façade on a building in Manchester, UK, where the average outdoor temperature was 10°C. That helped protect the wall structure from temperature fluctuation, since the ivy green façade increased the external surface temperature by 1.7°C, which reduced the outgoing heat transfer of the wall by 8%. In addition, Cameron et al. (2015) studied the green façade covering all the walls of cuboids in Reading, Berkshire UK under extremely winter conditions where there was snow. The green façade helped to reduce the energy consumption by 20% to heat the inner space of studied cubes compared to the unplanted cubes. In contrast, Coma et al., 2016 studied the green roof in the winter season. The incident solar radiation varied from 0 to 400 W/m^2, while the outdoor air temperature and relative humidity had an average of 7°C and 90%, respectively. They found that the green roofs consumed more electric power, by an average of 10% than that of the reference roof due to the high thermal conductivity of the green roofs because of the stored water content in the soil. The most dominating parameter the excess of moisture content, which adds more thermal conductivity, in the green roofs compared to other vertical greenery systems. This results in more energy consumptions by using green roofs, while others save energy consumption.

c. Diurnal variation

The diurnal change varies according to the studies location or climates and seasons. The diurnal range of direct solar radiation reaches the widest in winter and narrowest in summer, with medium values for spring and autumn. For all seasons, the sunny day gets the widest diurnal range, with suppression on a cloudy day, and diminishing to almost zero on a rainy day. For instance, for the green roofs, Coma et al. (2016) measured the interior roof surface in three cases without green roofs and with green roofs with different drainage layers in the temperature climate of Spain in the winter season. Both green roofs showed lower interior roof temperature compared to the referecne roof in the cold weather. However, the electrical power consumption to heat the room was more in the green roofs compared to the reference roof. When the outdoor temperature varies from -0.1°C to 13°C, the interior surface temperature of the reference roof varied from 12°C to 14°C, while the green roofs varied from 10°C to 12°C. In the summer season, the cooling load of the green roofs was less than that of the reference roof. Similar trends in the studies of (Theodosiou, 2003; Ascione et al., 2014) have proven similar results in both a summer and a winter day.

For the diurnal variation effect on the green façade systems, Bolton et al. (2014) explored the external surface temperature variation of applying the green façade to the building envelope in the winter season of Manchester, UK. The outdoor air temperature varied from 6°C to 10°C. The maximum and the minimum external surface temperature of a bare wall was 12°C and 8°C, respectively, while the maximum and the minimum external surface temperature of a vegetated wall was 10°C and 9.8°C at the same time day and night. At night the plant would reduce heat loss both by reducing the escaping the long wave of radiation from the external wall surface and protecting the wall from the wind, which reduces the convective heat loss. A similar trend was found in (Cameron et al., 2015) study in winter season where a room covered by green façade consumed about 20% less than that of the uncovered one.

For the living wall systems, Chen et al., 2013 used a living wall system with an air space in China of subtropical climate during the a summer season. The exterior and interior temperature of the living wall has a much smaller temperature fluctuation compared to the bare wall. During the daytime the exterior temperature of vegetated wall is much less than that of the bare wall at 20°C, while at night, the bare wall was cooler than the living wall by about 1°C. The air layer was cooler than the outdoor air by 10°C, which results in saving energy consumption by 0.4 kWh less than that of the space without the greenery system. Another example, Olivieri et al. (2014) explored diurnal variation in different seasons in Colmenar Viejo, Spain of hot summer Mediterranean climate. The temperature of a bare wall during the day was higher than that of living wall but less during night time in summer. During the spring and autumn season, the difference between the exterior surface temperature of the bare wall and the living wall during the daytime was 12°C and 10°C, respectively, and almost zero during the night time.

d. *Spatial variation*

Spatial variation refers the orientation of the vertical greenery systems on the wall structure such as north, south, east and west. Since the incident solar radiation on a vertical surface depends on the four directions, the effect of vertical greenery systems also depends on the directions of the walls. For example, Fernandez-bregon et al. (2012) installed a living wall in Almeria, Spain of hot desert climate. Two living walls in north and south directions were compared with bare walls at the same directions. They found that the southern living wall was higher than the northern one by 2°C, and both of them were less than that of the bare wall by 8°C in the north and by 2°C in the south direction. That is because the hourly global average solar radiation has been reduced by 32 W/m^2 in the south and 11 W/m^2 in the north.

Another example related to the green façade, Perez et al. (2011) investigated the location of the green façade walls in different directions (in the northwest, southwest, and southeast facades) and measured the building wall surface temperature. They found that the green façade temperature of the southeast façade was the highest with an average of 32°C while the northwest façade was the lowest of 28°C, and both of them were lower that the wall without plants having an average of 40°C. Similar to Jim and He (2011) where the south living wall was higher that the north living wall and both of them were lower the the bare wall. The south bare wall gets the highest value of hourly global solar radiation in summer (1170 W/m^2), followed by north bare wall (1030 W/m^2), while the south and the north green wall received solar radiation of 890 and 730 W/m^2, respectively.

4.3.5.2 Leaf area index

The leaf index describes the density of the plant layer covering the wall surface and affects the reduction of the external surface temperature and heat flux reduction. Different leaf area index was investigated under the same relative humidity and incident solar radiation. For instance, Susorova et al. (2013) used different leaf index values ranged from 0 to 4 to evaluate numerically the thermal performance of a green façade. The results showed that the reduction in the external surface temperature varied between 0.8°C and 13.1°C, while the heat flux reduction ranged from 2 W/m^2 to 33 W/m^2. The zero leaf index means that there is no leaf coverage on the surface, but there was a plant stem sticking to the wall which added a small amount of thermal resistance and helps in a slight heat reduction. Also, Sailor (2008) found that the higher leaf area of 5 increased gas consumption in the winter and reduced electricity consumption in the summer. Similarly, Carlos (2015) investigated the living wall under variable leaf area index in winter; he found that decreasing the leaf area index (from 5 to 0.5) will increase the reduction of the heating load by

1%. The reason for that, the plant layer functions as a solar barrier reducing the absorption of solar energy throughout the day. A lower solar reflection and also higher solar absorptance of the soil allow the useful solar heat to increase the outer surface temperature.

4.3.5.3 Moisture content

The moisture content is another factor, which comes from three main items: evapotranspiration process of plants, the amount of precipitation, and the irrigation process. The majority of studies have linked the reason for the moisture content to the precipitation or the relative humidity of the ambient air since the amount of moisture from evapotranspiration process is very small compared to the amount of precipitation. When the ambient relative humidity is low, plants significantly decrease the rate of evaporation as a way to protect themselves from dehydration (Vanderzanden, n.d.). When the relative humidity is high, the rate of evaporation from plants significantly increases. This process is controlled by stomatal pores on the plant surface, which open and close depending on surrounding humidity. For the green roofs, Alexandri and Jones (2008) observed the evaporative heat fluxes from the concrete roof of a range from -46.3 to 170.6 W/m^2 and from a green roof of a range of -593.2 to -26.4 W/m^2.

For the green façade systems, Different relative humidities were investigated under the same incident solar radiation (Susorova et al., 2013). The range of the outdoor relative humidity was from 20% to 100% the reduction of external surface temperature varied between 11.9°C to 14.2°C and the heat flux reduction changed from 30 W/m^2 to 36 W/m^2. The construction of the green façade is to cover the wall with climbing plants directly without a substrate layer since it is on the ground. The heat reduction refers to the radiation and convective heat transfer, while the latent heat is almost negligible since plant leaves absorb a small amount of vapour water during the saturation air (100% relative humidity). In the case of extremely cold weather as in (Cameron et al., 2015), the use of green facades helped to keep the wall dry during rainfall periods. Plant leaves intercepted and deflected precipitation away from the wall. However, they caused increasing in energy consumption in winter to warm the selected place.

The living wall systems, consiste of an additional substrate and support layers to the vegetation layer. The substrate layer acts as moisture sink, which adds more thermal resistance to the wall. In Carlos (2016), reducing the saturation volumetric moisture content of the soil increased the reduction of heating load about 7%. However, during the raining day and in winter, the thermal resistance of the wet soil increased as adding another layer of insulation. The overall thermal conductivity of the dry soil and the wet soil were 1.7 and 1.2 W/m^2.K, respectively. Therefore, the wet soil was able to reduce heating load more compared to the dry soil.

Adding a layer of air space behind the living walls help in lowering the relative humidity in the air space and consequently in the indoor place. For example, Chen et al. (2013) investigated the relative humidity in different air spacing. They found that the average relative humidity of the sealed air layer is 88.2%, much higher than the open air layer (74.7%) and the ambient air (75.6%). The air space layer provide natural ventilation to lower the relative humidity.

4.3.6 Laboratory and field studies

The majority of studies have conducted laboratory studies that showed a significant impact of plants on the reduction of external surface temperature as well as heat transfer through the walls and roofs. Few investigations have performed in a field study. Tseng et al. (2013) measured the energy consumption of a real, occupied, office-building in Taiwan of humid subtropical climate. A large size living wall was covered a whole west side of the building. The results showed that the vertical garden saved energy consumption of the building with an average of 8% daily, and external surface temperature reduction was 2.2°C in summer. However, the energy saving in winter was minimal. The total saving of energy consumption was 1.5 % annually. In addition, Mangone and van der Linden (2014) measured the energy consumption of using a green shading for a courtyard inside an office building in Ghana, which has a tropical savanna climate. The green shading was able to reduce the temperature of the courtyard by an average of 1.1 °C during the day and a maximum of 2.0 °C on the peak summer day. It also reduced the peak cooling loads of the air conditioned spaces that are adjacent to the courtyard by an average 21.3%, which was less than that of a metal shading by 2.3%. When 5% of building occupants occupy the courtyard, the cooling load is reduced by an additional 0.5%. Using large surface area of greenery systems on the wall structure has a relative effect on energy saving in real buildings.

The building enclosure elements that can accommodate greenery are only responsible for a certain fraction of the heating and cooling load of a whole building. Thus, there is an upper bound on how much greenery can reduce energy use, and further that reductions are very specific to a building type, climate, and exposure to solar radiation.

4.3.7 The life cycle analysis

We only focused on the findings from laboratory and field experiments, so we did not capture any study related the life cycle analysis, but it is briefly discussed to assess the sustainability of use the greenrey systems. For the roof, the life cycle cost was performed by Wong et al. (2003). The life cycle costs consist of structural cost, which is the cost of constructing roof decks with and without roof gardens, initial costs, maintenance and replacement costs. They found that the initial cost of extensive green roof systems was substantially higher than that of a reference roof due to the excess material of a substrate, drainage, and plants, and it varies according to the selection of planting and a type of structure. However, the life cycle cost can be reduced by adding the benefits from energy savings from the green roof system.

In addition, Feng and Hewage (2014) established a comparison of the life cycle analysis between the green façade and two types of living walls: those using felt layer and planter box systems. The life cycle analysis includes the initial cost, and the costs of manufacturing, construction, and maintenance. They found that the green façade system is more economic and an environmentally sustainable system than other systems, which is considered as system.

Moreoever, Ottelé et al. (2011) found that the living wall system based on felt layers used twice the amount of watering rather than planter-boxes living wall and much more than green facades, its waste cannot be recyclable, and it was necessary to replace the panels five times in a service life of 50 years. It also has a high environmental burden due to the durability aspect and the materials used. However, the green façade has a very small influence on the total environmental burden, and without any additional structuring material involved. The sustainability of a system depends on the difference of the environmenal benefits (such as energy savings) and burdens (using of additional materials, manufacturing, maintenance, and recycling). It was found that the green façade without using trilles on the walls to support climbing plants can always be a sustainable choice since it has less environmental burden compared to other greenery systems. A similar trend was also found in the study of Perini and Rosasco (2013).

4.3.8 Alternative methods

Comparing other alternative ways to save energy, Floride et al.(2002) presented different insulations and their effect on cooling and heating load in a full-scale house with four external walls and a window on each wall. The cooling load of the house substaintially decreased by

42.9% and 51.5 % and and heating load decreased by 59.3% and 66.5% for 25 mm roof insulation only and 50 mm roof and all walls insulation. Similarly, Al-Sanea (2002) investigated different different types of roof insulations with different insulation materials. Using a light weight of foam concrete type, reduced the heat transfer load by 45%, while the heat transfer load decreased by an average of 27% by using a 5-cm thick insulation materials. Adding artificial insulation materials into walls and roofs showed a greater impact on energy saving (heating and cooling loads) compared to the greenery systems discussed above.

In conclusion, plants can absorb incident solar radiation, and they are able to reduce the external surface temperature of the building envelope resulting in the reduction in heat transfer through the building envelope. They have a great impact on hot and dry climates since they were able to block high solar radiation and produce the cooling effect from evapotranspiration process. Excessive amounts of moisture content due to precipitation can increase the heat transfer load since they add unwanted latent load needed to be removed. Plants also have a significant effect during the daytime more than in night time and summer more than in winter seasons. More foliage coverage on the wall or roof structure can have a greater effect of external temperature reduction than no or limited coverage. However, in real-location studies, the plants can have a relative impact on energy consumption in spite of covering a large surface area of the building envelopes that is because the thermal load of walls is less contributor to the overall thermal load of buildings compared to internal thermal loads and thermal load from glazing systems.

4.4 Impact of indoor plants on psychological status

Several studies have investigated the effect of indoor plants on psychological status by analyzing 20 articles in psychological research. I found that the indoor plants play an important role in psychological effects of occupants by improving the following: attention capacity, production, the performance of participants, anxiety reduction, and concentration based on their physical features and physical activities. In this section, the psychological effects of different feature of indoor plants is covered. A comparison is established between the psychological effects of the existence of indoor plants and other inanimate objects. Also the psychological effects of gardening activities are explored. In addition, the different psychological measurements are listed. Moreover, the research validation is discussed.

4.4.1 Physical features of indoor plants

The physical features of indoor plants include type, size, colour, smell, and foliage level. For example, Qin et al. (2014) investigated different kinds of plants with different levels of colour (green, tint and multi-colour), odour (no odour, slight scent, and strong scent) and size (small, medium and large). For the colour group, the green plants brought the highest degree of satisfaction compared with tint and multi-colour plants. For the odour group, participants who are subjected to the plants with slight scent were more relaxed then who were subjected to the plants with a strong scent. For the size group, the participants reported the most satisfaction for the small-size plants. In addition, Jang et al. (2012) provided similar results, since they investigated different coloured flowering plants (white, yellow, pink, and red) and green foliage potted plants. They found that green plants provided a comfortable environment since green stimuli had a more comforting influence than white, yellow, pink, or red stimuli. Also, plants with bright yellow flowers caused feelings of happiness. The environments containing green, white, or yellow flowers induced feelings of comfort, brightness, and pleasantness. However, the pink and red flowers provided strength, vibrancy, unease, and a fancy effect. In another study, Guéguen (2012) investigated the effect of using un-foliage plants compared to foliage plants in an office room on the awareness of global warming. The absence of foliage is associated with an increase in beliefs about global warming. In addition, the beliefs about global warming increased as soon as the number of indoor plants without foliage increased.

4.4.2 Comparison between the existence of plants with other objects.

The existence of indoor plants was compared with other objects such as artificial plants, pictures, and a window view to external landscape or gardens. Igarashi et al. (2015) established a comparison between artificial plants and real plants with the same species and size (yellow pansies of weak scent). They found that the visual stimulation with real flowers resulted in comfortable, relaxed and natural feelings when compared with artificial pansies. The real flowers significantly decreased sympathetic nerve activity compared with artificial flowers. The sympathetic nerve activity is measured using heart rate variability, which is the ratio of low-to-high frequency heart rate by fingertip acceleration pulse wave. However, no significant difference was observed between the effect of real and artificial flowers on the heart pulse rate of participants.

In comparing indoor plants with other inanimate objects, Evensen et al. (2015) compared the effect of live plants and inanimate objects on simulated office work in two cases with and without a window view in terms of fascination and restorative effect. They found that the presence of indoor plants led to higher levels of perceived fascination of the setting. However, indoor plants did not have superior restorative effects compared with inanimate objects (such as a picture) while performing tasks demanding directed attention, neither in a setting with a window view nor a setting without a window view. However, environmental enrichment with either plants or inanimate objects at the computer workstation seemed to provide a restorative effect. A similar study a natural viewing through a window, Benfield et al. (2015) investigated the restorative effects of the visual access to natural environment on students and compared to a viewing a concrete wall. They found that classrooms with visual access to a natural environment promoted positive classroom outcomes. Students with a natural view rated the course curriculum, classroom resources, and classroom materials more positively than students with no natural view. In addition, Lin et al. (2013) to examine how interior amenities surrounding the workplace might moderate hospital professionals' work stresses on their health. Such interior amenities included indoor plants, aquariums, music, art and exhibitions, and private or personalized spaces, that surrounded health care professionals as moderators. During the self-reporting survey, they found that indoor plants have a moderating effect on physician-patient relationship stresses for a short period during work breaks as well as other amenities.

In the case of the lack of windows, Bringslimark et al. (2011) used cross-sectional survey data from 385 Norwegian office workers to investigate whether such compensation occurs for no-window offices. There were two dependent variable personal plants and personal pictures of nature. They indicate that having personal indoor plants was more common among those with fewer work demands, those who had other decoration items, and those without a window. Office workers who lacked a window view were more likely to place nature plants more than having pictures of nature and more than office workers who had a window view.

4.4.3 Physical activity with plants

Gardening activities have health improvement since they were used as a horticultural therapy. People remain connected to the computer environment through getting information or entertainment. This causes a great deal of stress called technostress (Tiemo and Ofua, 2010;

Walz, 2012). To provide a suitable treatment, Lee et al. (2015) examine the physiological benefits of indoor plants in modern people who excessively use a personal computer in studying and working. They allowed the participants to perform some gardening activities such as planting and transporting, and some computer tasks. They measured the autonomic nerve system activity by measuring the heart rate variables and quantified the psychological changes during the contact with plants by using surveys. The autonomic nerve system regulates the functions of our internal organs such as the heart, stomach and intestines, and controls muscles and glands. It contains parasympathetic nerve system, sympathetic nerve system, and enteric nerve system. The heart rate variability indicates the variation of both parasympathetic and sympathetic nerve system. They found that indoor plants have positive physiological effects on the autonomic nervous system by decreasing sympathetic activity which indicates lowering the stress. Also, they found that the participants had positive feelings when interacting with indoor plants. However, the computer tasks increased diastolic blood pressure and sympathetic nervous system activity.

In addition, a similar approach was applied in a work office, Gray and Birrell (2014) introduced the biophilic design into a lean workplace. The biophilic design is an attempt to bring nature back into the architecture. The workers planted and performed gardening activities as part-time during their work time, and brought the plants in boxes into their workplace. The researchers took series of demographic questions and performed interviews and took observations of site workers. They found that incorporating the aspects of biophilic design has a strong positive effect on cognitive, social, psychological and physical health benefits for workers by boosting productivity, reducing stress, enhancing well-being, fostering a collaborative work environment and promoting workplace satisfaction.

Applying the horticultural therapy, Detweiler et al. (2012) presented a literature review about using the horticultural therapy on elderly by exposing to gardens and sometimes performing simple gardening activities; they found that indoor gardening has been reported to be effective for improving sleep, lowering agitation, and stimulating cognition in dementia patients. Also, the horticultural therapy can be used as a psychiatric rehabilitation in dementia unit residents to improve the quality of life of elderly. It helps improving the sense of responsibility, attention, memory, and social interaction. Also, it can reduce stress and increase feelings of calm and relaxation.

Overall, the indoor plants have been used in psychological research as a potential natural therapy. They can provide many psychological and physiological benefits, such as reducing stress, enhancing restoration, improving attention, increasing concentration, enhancing productivity, and providing the social connection. These benefits were measured by surveys and psychological measurement devices by conducting different experimental designs by focusing on specific groups or sectors with small and large sample size and not extending the research to a major population to satisfy the external validity.

4.5 Integration Scenarios

In the previous sections, I discussed the impact of indoor plants on the indoor air quality, energy use, and psychological status. Each was presented in separate sections. In this section, I present two scenarios to combine these effects in one case.

(a) The first scenario considers the indoor potted plants. If an office worker brings a potted plant to his office, or a householder brings a potted plant to his house, the general effects of the indoor potted plant are the following:

In terms of indoor air quality, the indoor plants absorb a small amount of VOCs in the office or house, and emit a small amount of other VOCs and microorganisms. However, their effect on indoor air quality is negligible.

In terms of energy use, the indoor potted plants add a negligible amount of latent heat due to evapotranspiration and irrigation incomparable to the latent heat from a person with all kinds of activities. Therefore, the indoor potted plants have a negligible effect on energy use.

In terms of psychological effects, the potted plant will enhance the psychological status of the person in different ways as long as it is placed in the level of vision, not blocking the window view and the mobility in the room, has their preferable colours (e.g., green leaf to provide relaxation and concentration, yellow flower to provide happiness, etc.). Also the person is taking care of the plant by performing gardening activities (watering, trimming dead leaves, transplanting, and touching the soil), which reduce anxiety and provide calmness and concentration, and increase attention.

Another case of adding more indoor potted plants should be consider. The impact of increasing the amount of plants will be different compared to the previous case. In terms of the indoor air quality, the indoor plants may have the ability of removing air pollutants since the CADR value will increase. Also, the emission rates of other VOCs and microorganisms can be increased, which might affect human health. That is because the increase of potted plants will affect the environmental conditions by increasing the indoor relative humidity and slightly changing the indoor air temperature, which is a suitable environment of microorganism reproduction. However, the excessive combination of pollutant removal and emission by indoor plants is not clear and needs investigation to assess which mechanism has more contribution to the indoor air quality. For the energy use, the excessive amount of indoor plants may slightly vary the environmental conditions (relative humidity and indoor air temperature). This will slightly increase the energy consumption of the house to overcome the excessive latent heat caused by plants without compromising the environmental condition of growing the indoor plants. For the psychological effects. The excess amount of the indoor plants can provide psychological discomfort since they obstacle the occupant mobility and vision and block the indoor air movement.

(b) The second scenario considers the greenery systems on a building enclosure. The general effects of the greenery systems are the following:

In terms of indoor air quality, the greenery systems are located outside of the building on external walls and on the roof. The indoor air quality is directly not affected by such systems. However, they are effective on the outdoor air surrounding the building by reducing inorganic gaseous compounds such as carbon dioxide. If the building is equipped by an HVAC system that includes a ventilation system. The indoor air quality may be indirectly affected since the outdoor air concentration will be reduced.

In terms of energy use, in the summer season, the greenery systems can reduce the external surface temperature of the surfaces that are covered by vegetation in the summer season. This reduction will result in reducing the heat transfer through the building enclosure in which reduces energy consumption as long as the vegetation is covering a large surface area of the walls and the roof. However, in the winter season, the vertical greenery system, such as a living wall and green façade, reduce the surface temperature fluctuation and slightly increase the external surface temperature resulting in reduction of outgoing heat transfer to the outdoors, generally decreasing the heating load in the winter. For the green roofs, the interior surface temperature is reduced, which leads to more energy consumption because of more heating load. The annual saving in energy consumption varies according to the climate and location since the annual saving is higher in temperate and arid climate than that in continental climates.

In terms of psychological effects, the greenery systems are located on the external walls and roof. The easy access to outdoors will enhance the psychological status of the occupant at the level of vision. This accessibility can be performed by providing a nature view through a window, or providing areas of paving and seating.

Overall, the indoor plants can affect the psychological status of occupants and have negligible effect on indoor air quality and energy use. However, the excess indoor plants may have a slight influence on all the categories. While the greenery systems can provide unknown effect on indoor air quality and slightly reduce energy consumption of a building way under certain conditions according to climate, orientation and building type. They can also slightly impact the psychological status as long as they are located in the level of vision and have outdoor accessibility.

The current thesis has some limitations. It has focused on certain group of articles experimental studies and under certain period. Limited studied have conducted field studies. Each category has been investigated as separate discipline, which was challenging to combine them in one thesis. The scenarios are limited to two cases in a house excluding other scenarios such as commercial and industrial to assess the impacts of the plants, although there is no need to provide such cases because the limited impact of plants.

In this chapter, the impacts of the indoor plants are discussed on three categories: indoor air quality, energy use, and psychological status as well as we provided integration scenarios to assess the overall all impact of indoor plants the occupants. Each section has provided deep discussion of parameters and their variation followed by a conclusion of each. The overall conclusion will be presented in the next chapter.

Chapter 5 Conclusion

This thesis investigated the impact of indoor plants in three categories: indoor air quality, energy use, and psychological status. In this chapter, we conclude based on the findings and discussion for each category with the same order as presented in the thesis but in five themes as the following:

1. Pollutant removal
    - Indoor plants have higher removal efficiencies only in sealed chambers in laboratory studies
    - Indoor plants have very negligible CADR value compared to any air cleaner devices.
    - The effectiveness of indoor plants in a typical office is negligible
    - Indoor plants can remove the pollutants during long exposure time ranged between several hours to days to reach to the high removal efficiencies.
    - The decay rate of the pollutant removal by plants is very low.
    - Additional materials and microorganisms added to the soil and high intake air flow rate to the system can significantly increase the CADR, but the indoor plants (leaves and stem) are not necessarily related to the higher CADR.

2. Emission from plants
    - Plants emissions are important to its growth and survival. Plants can emit VOCs and microorganisms, among other pollutants.
    - Indoor plants emit a negligible amount of VOCs and most of these emissions are terpenoids.
    - Ozone can react with plant emissions, but these reactions are very limited compared to that of other indoor sources of terpenoids such as air fresheners, and consumer products.
    - Indoor plants emit a wide range of microorganisms from the plant leaves and soil.
    - Most of the studies have focused on fungi, and few have investigated bacteria.

- The bacterial load generally decreases, while the fungal load increases by adding indoor plants to a room.
- The most dominant fungal genera found in indoor environments with plants are *Cladosporium*, *Acremonium*, and *Alternaria* and are similar to the outdoor fungal spore genera.
- Bacterial species of *Legionella pneumophillia* usually is found in tap water and thus could be found during plant watering. However, this species was not detected in the included investigations.
- Many factors affect plant-associated fungi concentrations indoors such as external agitation including watering, air movement, type of soil, and high indoor relative humidity.
- The emission of microorganisms from indoor plants is low compared to other indoor sources, including occupants and their activities and pets.

3. Energy use
    - Greenery systems are investigated in studies of energy use because indoor plants have no mechanism to impact energy use.
    - Three general greenery systems were investigated: green roofs, green façades, and living wall systems.
    - The greenery systems are constructed by adding layers of vegetation, substrate, and supporting for vertical systems such as living walls and drainage systems for systems such as green roofs. These layers add thermal resistance to the building envelope to decrease the overall thermal conductivity.
    - The effect of greenery systems varies according to the climate and weather change, the diurnal change, the orientation of the systems, the leaf index, and the moisture content.
    - The greenery systems are generally more effective during the summer season and in arid and temperate climate since the vegetation can absorb a large amount of the incident solar radiation. This leads to decrease the external surface temperature and the heat transfer through the wall and roof structure.

- The vertical greenery systems are effective in west, south, and southeast orientations which receive higher incident solar radiation compared to other orientations.
- In the winter season, vertical greenery systems (green facades, and living walls) can also increase the external surface temperature, which reduces the outgoing heat transfer through the walls resulting in a reduction of the heating load of a building.
- However, also in the winter season, the green roofs can also decrease the interior roof surface temperature resulting in an increase in the heating load of a building. This temperature decrease is caused by moisture retention in the substrate.
- The high leaf area index, the vegetation coverage on a surface, leads to more reduction in external surface temperature and more reduction in heat transfer, resulting in less energy consumption.
- Higher moisture content in the greenery systems increases the thermal conductivity and increases the latent load resulting in increasing the cooling load of a building in the summer season and heating load in the winter season. However, it may provide a good cooling effect since it mitigates the external surface temperature in the arid an dry climate.
- The results of using greenery systems in laboratory studies (ranges from 10% to 30% energy savings) are more effective than that in a real-life application (ranges from 1.5% to 9%).
- The life cycle analysis studies have shown that the direct green façade is more sustainable than all living wall systems because of supporting material and maintenance.
- The costs of green roofs are more sustainable than a reference roof because of energy saving. The costs may increase according to the types of construction material and other auxiliary accessories for accessibility.
- Alternative methods such as adding 50 mm insulation to the roof and walls will generally save more building energy than the greenery systems.

4. Psychological impacts
    - Previous studies have proven that indoor plants can provide psychological benefits to occupants
    - Indoor plants can improve attention, increase concentration, improve restoration for a short time, reduce stress, promote satisfaction, and improve productivity.
    - The colour and scent of plants can influence their impact on psychological status.
    - Smaller plants may provide more satisfaction than medium and large sizes.
    - The indoor plants without leaves can provide awareness of global warming.
    - Gardening activities and biophilic design enhance concentration and provide relaxation, and increase productivity.
    - Indoor plants in workplaces and classrooms promote workplace satisfaction and improve productivity.
    - The psychological measurement showed the psychological improvement after participants are exposed to the plants.
    - Generally, study subjects need to see the plants to gain any benefit.
    - Some confounding variables affect the internal validity of many psychological studies about the plants. These variables include the visual experience of the control group to the indoor plants because of the office layout design of a building.

5. Integration scenarios
    - Adding indoor plants into a room will have a negligible effect on indoor air quality and energy use, but will be effective in enhancing the psychological status of the occupants if the occupant will take care of the potted plant and it is located on the level of vision.
    - Adding a greenery system on the external roof or wall may remove and/or emit a small amount of pollutants, VOCs, and microorganisms to the outdoors. However, the indoor air quality might not be affected.
    - The greenery systems will reduce the external surface temperature and heat transfer in the summer season and slightly in the winter season. This may lead to

the annual saving of energy consumption for a larger surface area covered by vegetation.

References

Aenchbacher, W., Park, S., Dunda, S., & Best, T. (2013). Broadened perceptions of engineering in tenth grade students through a biowall design project. *In 2013 IEEE Frontiers in Education Conference (FIE)*, 1336–1342.

Aharoni, A., Jongsma, M. A., & Bouwmeester, H. J. (2005). Volatile science? Metabolic engineering of terpenoids in plants. *Trends in Plant Science*, 10(12), 594–602.

Aira, M. J., Rodríguez-Rajo, F. J., Fernández-González, M., & Jato, V. (2011). Airborne pollen of ornamental tree species in the NW of Spain. *Environmental Monitoring and Assessment*, 173(1–4), 765–775.

ANSI/AHAM AC-1-2006. Test Method for Rating Performance of Portable Room Air Cleaners.

ASHRAE, A. (2001). Standard 62-2001. Ventilation for acceptable indoor air quality.

Atkinson, R. and Arey, J. (2003). Gas-phase tropospheric chemistry of biogenic volatile organic compounds: A review. *Atmospheric Environment*, 37(SUPPL. 2).

Aydogan, A. and Montoya, L. D. (2011). Formaldehyde removal by common indoor plant species and various growing media. *Atmospheric Environment*, 45(16), 2675–2682.

Bakker, I. and van der Voordt, T. (2010). The influence of plants on productivity. *Facilities,* 28(9/10), 416–439.

Baosheng, K., Shibata, S., & Sawada, A. (2009). Air Purification Capability of Potted Phoenix Roebelenii and Its Installation Effect in Indoor Space. *Sensors and Materials*, 21(8), 445–455.

Barberán, A., Dunn, R. R., Reich, B. J., Pacifici, K., Laber, E. B., Menninger, H. L., ... & Fierer, N. (2015). The ecology of microscopic life in household dust. In *Proc. R. Soc. B,* 282(1814), 201511-39.

Bell, M. L., Dominici, F., & Samet, J. M. (2005). A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. *Epidemiology (Cambridge, Mass.)*, *16*(4), 436.

Benfield, J. A., Rainbolt, G. N., Bell, P. A., & Donovan, G. H. (2013). Classrooms with nature views: Evidence of differing student perceptions and behaviors. *Environment and Behavior*, 47, 140–157.

Bolton, C., Rahman, M. A., Armson, D., & Ennos, A. R. (2014). Effectiveness of an ivy covering at insulating a building against the cold in Manchester, U.K: A preliminary investigation. *Building and Environment*, 80, 32–35.

Bringslimark, T., Hartig, T., & Patil, G. G. (2009). The psychological benefits of indoor plants: A critical review of the experimental literature. *Journal of Environmental Psychology*, 29(4), 422–433.

Burge, H. A., Solomon, W. R., and Muilenberg, M. L. (1982). Evaluation of indoor plantings as allergen exposure sources. *The Journal of Allergy and Clinical Immunology*, 70(2), 101–108.

C2ES. (2013). Residential and Commercial Emissions in the United States. Retrieved from http://www.c2es.org/energy/use/residential-commercial

Cameron, R. W., Taylor, J., & Emmett, M. (2015). A Hedera Green Façade – Energy Performance and Saving Under Different Maritime-Temperate, Winter Weather Conditions. *Building and Environment*, 92, 111–121.

Campbell G.S. and Norman J.M. (1998). An introduction to environmental biophysics. New York: Springer.

Carlos, J. S. (2015). Simulation assessment of living wall thermal performance in winter in the climate of Portugal. *Building Simulation*, 8(1), 3–11.

Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, 42(10), 1582–1591.

Chen, H. C., Wang, C. H., Chen, K. S., & Chang, T. L. (2014). Analysis and construction of stress relief model for healthy indoor environments. *Quality and Quantity*, 48(4), 2053–2067.

Chen, Q., Li, B., & Liu, X. (2013). An experimental evaluation of the living wall system in hot and humid climate. *Energy and Buildings*, 61, 298–307.

Chen, W., Zhang, J. S., & Zhang, Z. (2005). Performance of air cleaners for removing multiple volatile organic compounds in indoor air. *ASHRAE Transactions: Symposia*, 111 PART 1, 1101–1114.

Cheng, C. Y., Cheung, K. K. S., & Chu, L. M. (2010). Thermal performance of a vegetated cladding system on facade walls. *Building and Environment*, 45(8), 1779–1787.

Chun, S., Yoo, M. H., Moon, Y. S., Shin, M. H., Son, K.-C., Chung, I., & Kays, S. J. (2010). Effect of Bacterial Population from Rhizosphere of Various Foliage Plants on Removal of Indoor Volatile Organic Compounds. *Korean Journal of Horticultural Science & Technology,* 28(3), 476–483.

Collins, C. D., Bell, J. N. B., & Crews, C. (2000). Benzene accumulation in horticultural crops. *Chemosphere*, 40, 109–114.

Coma, J., Pérez, G., Solé, C., Castell, A., & Cabeza, L. F. (2014). New green facades as passive systems for energy savings on buildings. *Energy Procedia*, 57, 1851–1859.

Coma, J., Pérez, G., Solé, C., Castell, A., & Cabeza, L. F. (2016). Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renewable Energy*, 85, 1106–1115.

Cruz, M. Dela, Christensen, J. H., Thomsen, J. D., & Muller, R. (2014). Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. *Environmental Science and Pollution Research*, 21, 13909–13928.

Cruz, M. Dela, Müller, R., Svensmark, B., Pedersen, J. S., Christensen, J. H., Dela Cruz, M., …Svensmark, B. (2014). Assessment of volatile organic compound removal by indoor plants-a novel experimental setup. Environmental Science and Pollution Research, 21(13), 7838–7846.

Dales RE, Zwanenburg H, Burnett R, Franklin CA. (1991). Respiratory health effects of home dampness and molds among Canadian children. Am J Epidemiol. 134:196–203

Dales, R., Liu, L., Wheeler, A. J., & Gilbert, N. L. (2008). Public health: Quality of indoor residential air and health. *Cmaj*, 179(2), 147–152.

Darlington, A., Chan, M., Malloch, D., Pilger, C., & Dixon, M. a. (2000). The biofiltration of indoor air: Implications for air quality. *Indoor Air-International Journal of Indoor Air Quality and Climate*, 10(1), 39–46. J

Darlington, A., Dixon, M. A., & Pilger, C. (1998). The use of biofilters to improve indoor air quality: the removal of toluene, TCE, and formaldehyde. *Life Support & Biosphere Science,*5, 63–69.

De Kempeneer, L., Sercu, B., Vanbrabant, W., Langenhove, H. Van, & Verstraete, W. (2004). Bioaugmentation of the phyllosphere for the removal of toluene from indoor air. *Applied Microbiology and Biotechnology,* 64, 284–288.

Destaillats, H., Maddalena, R. L., Singer, B. C., Hodgson, A. T., & McKone, T. E. (2008). Indoor pollutants emitted by office equipment: A review of reported data and information needs. *Atmospheric Environment*, *42*(7), 1371-1388.

Detweiler, M. B., Sharma, T., Detweiler, J. G., Murphy, P. F., Lane, S., Carman, J., … Kim, K. Y. (2012). What is the evidence to support the use of therapeutic gardens for the elderly? *Psychiatry Investigation*, 9(2), 100–110.

Devlin, R. B., McDonnell, W. F., Mann, R., Becker, S., House, D. E., Schreinemachers, D., & Koren, H. S. (1991). Exposure of humans to ambient levels of ozone for 6.6 hours causes cellular and biochemical changes in the lung. *American journal of respiratory cell and molecular biology*, *4*(1), 72-81.

Dooling, K. L., Toews, K. A., Hicks, L. A., Garrison, L. E., Bachaus, B., Zansky, S., ... & Thomas, A. (2015). Active bacterial core surveillance for legionellosis-United States, 2011-2013. *MMWR Morb Mortal Wkly Rep*, *64*(42), 1190-1193.

Dopazo, A., Aira, M. J., Armisén, M., & Vidal, C. (2002). Relationship of clinical and aerobiological pollen data in the north-west of Spain. *Allergologie et Immunopathologie*, 30(2), 74–78.

Dudareva, N. et al. (2004) Biochemistry of plant volatiles. *Plant Physiol.,* 135, 1893–1902

Ege, M. J. et al. (2006). Prenatal farm exposure is related to the expression of receptors of the innate immunity and to atopic sensitization in school-age children. J. Allergy Clin. Immunol. 117, 817–823

Eumorfopoulou, E. A., and Kontoleon, K. J. (2009). Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. Building and Environment, 44(5), 1024–1038

Evensen, K. H., Raanaas, R. K., Hagerhall, C. M., Johansson, M., & Patil, G. G. (2013). Restorative elements at the computer workstation: A comparison of live plants and inanimate objects with and without window view. *Environment and Behavior*, 47(3), 288–303.

Feng, H., & Hewage, K. (2014). Energy saving performance of green vegetation on LEED certified buildings. Energy and Buildings, 75, 281–289.

Feng, H., & Hewage, K. (2014). Lifecycle assessment of living walls: Air purification and energy performance. *Journal of Cleaner Production*, 69, 91–99.

Fernandez-Bregon, N., Urrestarazu, M., Valera, D. L., Fernández-Bregón, N., Urrestarazu, M., & Valera, D. L. (2012). Effects of a vertical greenery system on selected thermal and sound mitigation parameters for indoor building walls. Journal of Food, *Agriculture and Environment*, 10(October), 1025–1027.

Fernandez-Canero, R., Urrestarazu, L. P., Franco Salas, A., & Franco-Salas, A. (2012). Assessment of the Cooling Potential of an Indoor Living Wall using Different Substrates in a Warm Climate. *Indoor and Built Environment*, 21(5), 642–650.

Fernández-Rivas, M., Benito, C., González-Mancebo, E., and Durana, D. A. (2008). Allergies to fruits and vegetables. *Pediatric Allergy and Immunology*, 19(8), 675– 681.

Ferro AR, Kopperud RJ, Hildemann LM. (2004). Source strengths for indoor human activities that resuspend particulate matter. Environ Sci Technol. 38: 1759–64.

Fisk W.J., Black D., Brunner G. (2011). Benefits and costs of improved IEQ in U.S. offices. *Indoor Air*, 21(5), 357–367.

Florides, G., Tassou, S., Kalogirou, S., & Wrobel, L. (2002). Measures used to lower building energy consumption and their cost effectiveness. *Applied Energy*, 73(3–4), 299–328.

Girman, J., Phillips, T., & Levin, H. (2009). Critical Review : How Well Do House Plants Perform as Indoor Air Cleaners ? *In Proceedings of Healthy Buildings*, 9-12.

Gillis, K. and Gatersleben, B. (2015). A Review of Psychological Literature on the Health and Wellbeing Benefits of Biophilic Design. *Buildings*, 5(3), 948–963.

Godish, T., & Guindon, C. (1989). An assessment of botanical air purification as a formaldehyde mitigation measure under dynamic laboratory chamber conditions. *Environmental Pollution*, 61, 13–20.

Goff S.A., Klee H.J. (2006). Plant volatile compounds: sensory cues for health and nutritional value? *Science* 311: 815–819.

Goodwin, C. J. (2002). Research in psychology: Methods and design. John Wiley & Sons. Gou, Z., & Lau, S. S. (2012). Sick building syndrome in open-plan offices. *Journal of Facilities Management*, 10(4), 256–265.

Gray, T., & Birrell, C. (2014). Are biophilic-designed site office buildings linked to health benefits and high performing occupants? *International Journal of Environmental Research and Public Health*, 11(12), 12204–12222.

Grant, A. M., and Wall, T. D. (2009). The Neglected Science and Art of Quasi-Experimentation. *Organizational Research Methods*, 12.

Guéguen, N. (2012). Dead indoor plants strengthen belief in global warming. *Journal of Environmental Psychology*, 32(2), 173–177.

Guieysse, B., Hort, C., Platel, V., Munoz, R., Ondarts, M., & Revah, S. (2008). Biological treatment of indoor air for VOC removal: Potential and challenges. *Biotechnology Advances*, 26, 398–410.

Haggag, M., Hassan, A., & Elmasry, S. (2014). Experimental study on reduced heat gain through green facades in a high heat load climate. *Energy and Buildings*, 82, 668–674.

Hansen, S. B., Olsen, S. I., & Ujang, Z. (2012). Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel. *Bioresource Technology*, 104, 358-366.

Hasegawa, Y., Asada, S., Katsube, T., & Ikeguchi, T. (2004). Analysis of Bioelectrical Potential When Plant Purifies Air Pollution. *IEICE Transactions on Electronics*, E87–C(12), 2093– 2098.

Hasegawa, Y., Uchida, H., Asada, S., Katsube, T., & Oyabu, T. (2002). Investigation of Air Pollution Purification Process by a Bioelectrical Potential Analysis. In Proceedings: *Indoor Air*, 700-705.

Hunter, A. M., Williams, N. S. G., Rayner, J. P., Aye, L., Hes, D., & Livesley, S. J. (2014). Quantifying the thermal performance of green facades: A critical review. *Ecological Engineering*, 63, 102–113.

Igarashi, M., Aga, M., Ikei, H., Namekawa, T., & Miyazaki, Y. (2015). Physiological and psychological effects on high school students of viewing real and artificial pansies. *International Journal of Environmental Research and Public Health*, 12(3), 2521–2531.

Jaafar, B., Said, I., & Rasidi, M. H. (2012). Evaluating the impact of vertical greenery system on cooling effect on high rise buildings and surroundings: a review. *Jurnal Ruas*, 9(2), 1–9.

Jaafar, B., Said, I., Reba, M. N. M., & Rasidi, M. H. (2013). Impact of Vertical Greenery System on Internal Building Corridors in the Tropic. *Procedia - Social and Behavioral Sciences*, 105, 558–568.

Jaakkola J, Jaakkola N, Ruotsalainen R. (1992). Home dampness and molds as determinants of respiratory symptoms and asthma in pre-school children. J Expo Anal Env Epid. 3:129–42

James, C. A., Xin, G., Doty, S. L., & Strand, S. E. (2008). Degradation of low molecular weight volatile organic compounds by plants genetically modified with mammalian cytochrome P450 2E1. *Environmental Science and Technology*, 42(1), 289–293.

Jang, H. S., Kim, J., Kim, K. S., & Pak, C. H. (2014). Human brain activity and emotional responses to plant color stimuli. *Color Research & Application,* 39(3), 307–316.

Jerrett, M., Burnett, R. T., Pope III, C. A., Ito, K., Thurston, G., Krewski, D., ... & Thun, M. (2009). Long-term ozone exposure and mortality. *New England Journal of Medicine*, *360*(11), 1085-1095.

Jin, C., Zhou, X., Zhao, H., Liu, X., Feng, K., In, C. U. J., … Eng, K. E. F. (2013). Comparison of Removal of Formaldehyde Capacity Between Hedera helix and Melissa officinalis. *Asian Journal of Chemistry*, 25(7), 3823–3826.

Jones, a. P. (1999). Indoor air quality and health. *Atmospheric Environment*, 33(28), 4535–4564.

Jumeno, D. and Matsumoto, H. (2015). Effects of foliage plants on human physiological and psychological responses at different temperatures. *AIP Conference Proceedings* 1649, 32, 32–40.

Kagi, N., Fujii, S., Horiba, Y., Namiki, N., Ohtani, Y., Emi, H., … Kim, Y. S. (2007). Indoor air quality for chemical and ultrafine particle contaminants from printers. *Building and Environment*, 42, 1949–1954.

Kampa, M. and Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2), 362–367.

Kaplan, R. and Kaplan, S. (1989). *The experience of nature: A psychological perspective*. New York, NY: Cambridge University Press.

Kehrl, H. R., Peden, D. B., Ball, B., Folinsbee, L. J., & Horstman, D. (1999). Increased specific airway reactivity of persons with mild allergic asthma after 7.6 hours of exposure to 0.16 ppm ozone. *Journal of allergy and clinical immunology*, *104*(6), 1198-1204.

Khoa, P. Van, Nang, B. Van, & Hao, N. T. B. (2013). Study on Gaseous Formaldehyde Removal Capability of Some Native Plant Species in Vietnam. *International Journal of Chemical, Environmental and Pharmaceutical Research*, 4(1), 1–7.

Kim, H.-H., Lee, J.-Y., Yang, J.-Y., Kim, K.-J., Lee, Y.-J., Shin, D.-C., & Lim, Y.-W. (2011). Evaluation of Indoor Air Quality and Health Related Parameters in Office Buildings with or without Indoor Plants. *Journal of the Japanese Society for Horticultural Science*, 80(1), 96–102.

Kim, H. J., Han, B., Kim, Y. J., Yoon, Y. H., & Oda, T. (2012). Efficient test method for evaluating gas removal performance of room air cleaners using FTIR measurement and CADR calculation. *Building and Environment*, 47, 385–393.

Kim, C. S., Alexis, N. E., Rappold, A. G., Kehrl, H., Hazucha, M. J., Lay, J. C., ... & Diaz-Sanchez, D. (2011). Lung function and inflammatory responses in healthy young adults exposed to 0.06 ppm ozone for 6.6 hours. *American journal of respiratory and critical care medicine*, *183*(9), 1215-1221

Kim, K. J., Jeong, M. I. I., Lee, D. W., Song, J. S., Kim, H. D., Yoo, E. H., … Han, S. W. (2010). Variation in Formaldehvde Removal Efficiency among Indoor Plant Species. *Control*, 45(10), 1489–1495.

Kim, K. J., Jeong, M. I., Lee, D. W., Song, J. S., Kim, H. D., Yoo, E. H., … Han, S. W. (2010). Variation in Formaldehvde Removal Efficiency among Indoor Plant Species. *Control*, 45(10), 1489–1495.

Kim, K. J., Kil, M. J., Jeong, M. Il, Kim, H. D., Yoo, E. H., Jeong, S. J., … Son, K. (2009). Determination of the Efficiency of Formaldehyde Removal According to the Percentage Volume of Pot Plants Occupying a Room. *Korean Journal of Horticultural Science &Technology*, 27(June), 305–311.

Kim, K. J., Kil, M. J., Song, J. S., Yoo, E. H., Son, K.-C., & Kays, S. J. (2008). Efficiency of Volatile Formaldehyde Removal by Indoor Plants: Contribution of Aerial Plant Parts versus the Root Zone. *Journal of the American Society for Horticultural Science*, 133(4), 521–526.

Kim, K. J., & Kim, H. D. (2008). Development of Model and Calculating Equation for Rate of Volatile Formaldehyde Removal of Indoor Plants. *Hort. Environ Biotechnol.*, 49(3), 1–7.

Kim, K. J., & Lee, D. W. (2008). Efficiency of Volatile Formaldehyde Removal of Orchids as Affected by Species and Crassulacean Acid Metabolism (CAM) *Nature. Hort. Environ Biotechnol.*, 49(2), 132–137.

Kim, K. J., Yoo, E. H., Jeong, M. Il, Song, J. S., & Young, L. S. (2011). Changes in the Phytoremediation Potential of Indoor Plants with Exposure to Toluene. *HortScience*, 46(12), 1646–1649.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, a M., Switzer, P., … Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, 11(3), 231–252.

Kreider, J. F., Curtiss, P. S., & Rabl, A. (2010). Heating and Cooling of Buildings Design for Efficiency, revised second edition. *Journal of Chemical Information and Modeling* (revised Vol. 53). CRC Press.

Laothawornkitkul, J., Taylor, J. E., Paul, N. D., & Hewitt, C. N. (2009). Biogenic volatile organic compounds in the Earth system. *The New Phytologist*, 183(1), 27–51.

Lee, M.-S., Lee, J., Park, B.-J., & Miyazaki, Y. (2015). Interaction with indoor plants may reduce psychological and physiological stress by suppressing autonomic nervous system activity in young adults: a randomized crossover study. *Journal of Physiological Anthropology*, 34(1),21.

Leech, J. A., Wilby, K., McMullen, E., & Laporte, K. (1996). The Canadian Human Activity Pattern Survey: Report of Methods and Population Surveyed. *Chronic Diseases in Canada*, 17(3–4), 118–123.

Leff J.W. and Fierer N. (2008). Volatile organic compound (VOC) emissions from soil and litter samples. *Soil Biology and Biochemistry* 40, 1629–1636.

Li, D. W., and Lamondia, J. (2010). Airborne fungi associated with ornamental plant propagation in greenhouses. *Aerobiologia*, 26(1), 15–28.

Lim, Y.-W., Kim, H.-H., Yang, J.-Y., Kim, K.-J., Lee, J.-Y., & Shin, D.-C. (2009). Improvement of Indoor Air Quality by Houseplants in New-built Apartment Buildings. *Journal of the Japanese Society for Horticultural Science*, 78(4), 456–462.

Lin, B. Y. J., Lin, Y. K., Juan, C. W., Lee, S., & Lin, C. C. (2013). Moderating role of interior amenities on hospital medical directors' patient-related work stresses. *Health Environments Research and Design Journ*al, 6(2), 77–92.

Lin, W., Yu, T., Chang, X., Wu, W., & Zhang, Y. (2015). Calculating cooling extents of green parks using remote sensing: Method and test. *Landscape and Urban Planning*, 134, 66–75.

Liu, Y.-J., Mu, Y., Zhu, Y.-G., Ding, H., & Arens, C. N. (2007). Which ornamental plant species effectively remove benzene from indoor air? *Atmospheric Environment*, 41, 650–654.

Lu, N., Pei, J., Zhao, Y., Qi, R., & Liu, J. (2012). Performance of a biological degradation method for indoor formaldehyde removal. *Building and Environment*, 57, 253–258.

Mahillon, V., Saussez, S., & Michel, O. (2006). High incidence of sensitization to ornamental plants in allergic rhinitis. *Allergy: European Journal of Allergy and Clinical Immunology*, 61(9), 1138–1140.

Mallany, J., Darlington, A., & Dixon, M. (2000). The biofiltration of indoor air II: microbial loading of the indoor space. *Conference on Biofiltration and Air*, (4), 5–10.

Malys, L., Musy, M., & Inard, C. (2014). A hydrothermal model to assess the impact of green walls on urban microclimate and building energy consumption. *Building and Environment*, 73, 187–197.

Mandal, J., & Brandl, H. (2011). Bioaerosols in Indoor Environment - A Review with Special Reference to Residential and Occupational Locations. *The Open Environmental and Biological Monitoring Journal*, 41(1), 83–96.

Mangone, G., Kurvers, S. R., & Luscuere, P. G. (2014). Constructing thermal comfort: Investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment. *Building and Environment*, 81, 410–426.

Mangone, G., and van der Linden, K. (2014). Forest microclimates: Investigating the performance potential of vegetation at the building space scale. *Building and Environment*, 73, 12–23.

Manso, M., and Castro-Gomes, J. (2015). Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews,* 41, 863–871.

Mazzali, U., Peron, F., Romagnoni, P., Pulselli, R. M., & Bastianoni, S. (2013). Experimental investigation on the energy performance of Living Walls in a temperate climate. *Building and Environment*, 64, 57–66.

Mebine, P., & Smith, R. (2009). Effect of pollutant decay on steady-state concentration distributions in variable depth flow. *Environmental Fluid Mechanics*, 9(6), 573–586.

Miller-Leiden, S., Lobascio, C., Nazaroff, W. W., & Macher, J. M. (1996). Effectiveness of in room air filtration and dilution ventilation for tuberculosis infection control. *Journal of the Air & Waste Management Association* (1995), 46(9), 869–882.

Morrison, G. C., & Nazaroff, W. W. (2002). Ozone interactions with carpet: secondary emissions of aldehydes. *Environmental Science & Technology*,*36*(10), 2185-2192.

Mosaddegh, M. H., Jafarian, A., Ghasemi, A., & Mosaddegh, A. (2014). Phytoremediation of benzene , toluene , ethylbenzene and xylene contaminated air by *D. deremensis* and *O.microdasys* plants. *Journal of Environmental Health Science & Engineering*, 1–7.

Mustafa, M. G., & Tierney, D. F. (1978). Biochemical and Metabolic Changes in the Lung with Oxygen, Ozone, and Nitrogen Dioxide Toxicity 1, 2.*American Review of Respiratory Disease*, *118*(6), 1061-1090.

Nazaroff, W.W. (2004) Indoor particle dynamics, Indoor Air, 14, 175–183.

Niu, J.L., Tung, T.C.W., Burnett, J. (2001). Quantification of dust removal and ozone emission of ionizer air-cleaners by chamber testing. Journal of Electrostatics 51–52, 20–24.

Nadia, S., Noureddine, S., Hichem, N., & Djamila, D. (2013). Experimental study of thermal performance and the contribution of plant-covered walls to the thermal behavior of building. *Energy Procedia*, 36, 995–1001.

Nazaroff, W. W., & Weschler, C. J. (2004). Cleaning products and air fresheners: exposure toprimary and secondary air pollutants. *Atmospheric Environment*, 38(18), 2841–2865.

Nejati, A., Shepley, M., Rodiek, S., Lee, C., & Varni, J. (2016). Restorative Design Features for Hospital Staff Break Areas: A Multi-Method Study. *Health Environments Research and Design Journal*, 9(2), 16–35.

Newkirk, D. W., Hutzel, W. J., Dana, M., & Qu, M. (2014). Energy Modeling of a Botanical Air Filter. *In 3rd International High Performance Buildings Conference at Purdue*, 3614:1-8.

Nieuwenhuis, M., Knight, C., Postmes, T., & Haslam, S. A. (2014). The Relative Benefits of Green Versus Lean Office Space: Three Field Experiments. *Journal of Experimental Psychology Applied*, 20(3), 199–214.

Niinemets, Ü., Loreto, F., and Reichstein, M. (2004). Physiological and physicochemical controls on foliar volatile organic compound emissions*. Trends in Plant Science,* 9(4), 180–186.

Olivieri, F., Olivieri, L., & Neila, J. (2014). Experimental study of the thermal-energy performance of an insulated vegetal facade under summer conditions in a continental Mediterranean climate. *Building and Environment*, 77, 61–76.

Orwell, R. L., Wood, R. L., Tarran, J., Torpy, F., & Burchett, M. D. (2004). Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water, Air, and Soil Pollution,* 157, 193–207.

Ottelé, M. (2011). *The Green Building Envelope Vertical Greening*. Department of Materials and Environment.

Ottelé, M., Perini, K., Fraaij, a. L. a, Haas, E. M., & Raiteri, R. (2011). Comparative life cycle analysis for green façades and living wall systems. *Energy and Buildings*, 43(12), 3419–3429.

Oyabu, T., Onodera, T., Kimura, H., & Sadaoka, Y. (2001). Purification Removing Ability of Interior Polluting Gas Plant for of Indoor-Air a Tin Chemicals Using. *Japan Society for Atmosphic Environment*, 36(6), 319–325.

Oyabu, T., Sawada, A., Onodera, T., Takenaka, K., & Wolverton, B. (2003). Characteristics of potted plants for removing offensive odors. *Sensors and Actuators B*, 89, 131–136.

Oyabu, T., Takenaka, K., Wolverton, B., Onodera, T., & Nanto, H. (2003). Purification characteristics of golden pothos for atmospheric gasoline. *International Journal of Phytoremediation*, 5, 267–276.

Owen,S.M., C. Boissard,and C. N. Hewitt (2001),Volatileorganic compounds (VOCs) emitted from 40 Mediterranean plant species: VOC speciation and extrapolation to habitat scale, *Atmos. Environ.*, 35(32), 5393–5409.

Peñuelas, J., Asensio, D., Tholl, D., Wenke, K., Rosenkranz, M., Piechulla, B., & Schnitzler, J. P. (2014). Biogenic volatile emissions from the soil. *Plant, Cell & Environment*, 37(8), 1866–1891.

Pérez, G., Coma, J. J., Martorell, I., Cabeza, L. F., & Pérez, G. (2014). Vertical Greenery Systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews*, 39, 139–165.

Pérez, G., Rincón, L., Vila, a., González, J. M., & Cabeza, L. F. (2011). Behaviour of green facades in Mediterranean Continental climate. *Energy Conversion and Management*, 52(4), 1861–1867.

Perini, K., Ottelé, M., Fraaij, a. L. a, Haas, E. M., & Raiteri, R. (2011). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment*, 46(11), 2287–2294.

Perini, K., Ottelé, M., Haas, E. M., & Raiteri, R. (2013). Vertical greening systems, a process tree for green façades and living walls. *Urban Ecosystems*, 16(2), 265–277.

Perini, K., & Rosasco, P. (2013). Cost-benefit analysis for green facades and living wall systems. Building and Environment, 70, 110–121. http://doi.org/10.1016/j.buildenv.2013.08.012

Porter, J. R. (1994). Toluene removal from air by Dieffenbachia in a closed environment. *Advances in Space Research*, 14(11), 99–103.

Prussin, A. J., & Marr, L. C. (2015). Sources of airborne microorganisms in the built environment. *Microbiome*, 3(1), 78.

Pulselli, R. M., Pulselli, F. M., Mazzali, U., Peron, F., & Bastianoni, S. (2014). Emergy based evaluation of environmental performances of Living Wall and Grass Wall systems. *Energy and Buildings*, 73, 200–211.

Qian J, Hospodsky D, Yamamoto N, Nazaroff WW, Peccia J. (2012). Size-resolved emission rates of airborne bacteria and fungi in an occupied classroom. Indoor Air. 22:339–51

Qin, J., Sun, C., Zhou, X., Leng, H., & Lian, Z. (2013). The effect of indoor plants on human comfort. *Indoor and Built Environment*, 23(5), 1–15.

Qin, J., Zhou, X., Sun, C., Leng, H., & Lian, Z. (2013). Influence of green spaces on environmental satisfaction and physiological status of urban residents. *Urban Forestry & Urban Greening*, 12(4), 490–497.

Raanaas, R. K., Evensen, K. H., Rich, D., Sjøstrøm, G., & Patil, G. (2011). Benefits of indoor plants on attention capacity in an office setting. *Journal of Environmental Psychology*, 31(1), 99–105.

Raji, B., Tenpierik, M. J., & van den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, 45, 610–623.

Riedler J, Eder W, Oberfeld G, Schreuer M. (2000). Austrian children living on a farm have less hay fever, asthma and allergic sensitization. Clin Exp Allergy. 30:194-200.

Riley, W. J., McKone, T. E., Lai, A. C. K., & Nazaroff, W. W. (2002). Indoor particulate matter of outdoor origin: Importance of size-dependent removal mechanisms. *Environmental Science and Technology*, *36*(2), 200–207.

Robinson, A. L., Subramanian, R., Donahue, N. M., Bernardo-Bricker, A., & Rogge, W. F. (2006). Source apportionment of molecular markers and organic aerosol. 3. Food cooking emissions. *Environmental Science and Technology*, 40(24), 7820–7827.

Rodgers, K. L., Hutzel, W., Dana, M., & Handy, R. (2012). Can Plants Save Money: A Look At The Biowall. *In International High Performance Buildings Conference at Purdue*, 3350:1-10.

Rodolfi, M., Lorenzi, E., & Picco, A. M. (2003). Study of the occurrence of greenhouse microfungi in a Botanical Garden. *Journal of Phytopathology*, 151(11–12), 591–599.

Safikhani, T., Abdullah, A. M., Ossen, D. R., & Baharvand, M. (2014). A review of energy characteristic of vertical greenery systems. *Renewable and Sustainable Energy Reviews*, 40, 450–462.

Silk BJ, Moore MR, Bergtholdt M, et al. (2012). Eight years of Legionnaires' disease trans- mission in travellers to a condominium complex in Las Vegas, Nevada. Epidemiol Infect 2012; 140:1993–2002

Sailor, D. J. (2008). A green roof model for building energy simulation programs. *Energy and Buildings*, 40(8), 1466–1478.

Saiyood, S., Vangnai, A. S., Thiravetyan, P., & Inthorn, D. (2010). Bisphenol A removal by the Dracaena plant and the role of plant-associating bacteria. *Journal of Hazardous Materials*, 178, 777–785.

Sakulyanontvittaya, T., Duhl, T., Wiedinmyer, C., Helmig, D., Matsunaga, S., Potosnak, M., …Guenther, A. (2008). Monoterpene and sesquiterpene emission estimates for the United States. *Environmental Science and Technology*, 42(5), 1623–1629.

Salonen, H., Lahtinen, M., Lappalainen, S., Nevala, N., Knibbs, L. D., Morawska, L., & Reijula, K. (2013). Physical characteristics of the indoor environment that affect health and wellbeing in healthcare facilities: a review. *Intelligent Buildings International,* 5(1), 3–25.

Sawada, A., Oyabu, T., Chen, L., Li, K., Hirai, N., Yurimoto, H., … Izui, K. (2007). Purification capability of tobacco transformed with enzymes from a methylotrophic bacterium for formaldehyde. *International Journal of Phytoremediation*, 9, 487–496.

Sawada, A., Oyabu, T., Yoshida, T., & Nagai, H. (2003). Removing capability for formaldehyde of plant growing in an activated carbon pot. *In SICE Annual Conference in Fukui*, 1549– 1554.

Sawada, A., Yoshida, T., Oyabu, T., Okada, A., Takenaka, K., & Manninen, O. (2002). Purification Effects of Plants for Indoor Air Pollution in a University Hospital. *Archives of Complex Environmental Studies*, 14, 3–4.

Scarpa, M., Mazzali, U., & Peron, F. (2014). Modeling the energy performance of living walls: Validation against field measurements in temperate climate. *Energy and Buildings*, 79, 155–163.

Singh, J. (1996). Impact of indoor air pollution on health, comfort and productivity of the occupants. *Aerobiologia*, 12(1), 121-127.

Smith, A., Tucker, M., & Pitt, M. (2011). Healthy, productive workplaces: towards a case for interior plantscaping. *Facilities*, 29(5/6), 209–223.

Soreanu, G., Dixon, M., & Darlington, A. (2013). Botanical biofiltration of indoor gaseous pollutants – A mini-review. *Chemical Engineering Journal*, 229, 585–594.

Sriprapat, W., & Thiravetyan, P. (2013). Phytoremediation of BTEX from indoor air by *zamioculcas zamiifolia*. *Water, Air, and Soil Pollution*, 224, 1482:1-9.

Staib F, Tompak B, Thiel D, Blisse A. (1978). Aspergillus fumigatus and Aspergillus niger in two potted ornamental plants, cactus (Epiphyllum truncotum) and clivia (Clivia miniata). Biological and epidemiological aspects. Mycopathologia, 66-27

Stangor, C. (2010). *Introduction to Psychology. Flat World Knowledge*, 860. Retrieved from http://ocw.mit.edu/ans7870/9/9.00SC/MIT9_00SCF11_text.pdf

Steiner, A. H., and Goldstein, A. L. (2007). *Biogenic VOCs. Volatile Organic Compounds in the Atmosphere*, 82–128.

Sunakorn, P., & Yimprayoon, C. (2011). Thermal performance of biofacade with natural ventilation in the tropical climate. *Procedia Engineering*, 21, 34–41.

Susorova, I., Angulo, M., Bahrami, P., & Brent Stephens. (2013). A model of vegetated exterior facades for evaluation of wall thermal performance. *Building and Environment*, 67, 1–13.

Taib, N., & Abdullah, A. (2012). Study of Landscape Gardens: Expectations and Users' Perceptions of a High-Rise Office Building. *Procedia - Social and Behavioral Sciences*, 50(July), 633–642.

Tan, C. L., Wong, N. H., & Jusuf, S. K. (2014). Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landscape and Urban Planning*, 127, 52–64.

Tani, A., & Hewitt, C. N. (2009). Uptake of aldehydes and ketones at typical indoor concentrations by houseplants. *Environmental Science and Technology*, 43(21), 8338–8343.

Tani, A., Kato, S., Kajii, Y., Wilkinson, M., Owen, S., & Hewitt, N. (2007). A proton transfer reaction mass spectrometry based system for determining plant uptake of volatile organic compounds. *Atmospheric Environment*, 41, 1736–1746.

Tarafdar, M., Pullins, E. B., & Ragu-Nathan, T. S. (2015). Technostress: negative effect on performance and possible mitigations. *Information Systems Journal*, *25*(2), 103-132.

Tarran, J., Torpy, F., & Burchett, M. (2007). Use of living pot-plants to cleanse indoor air -research review. *Proceedings of Sixth International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings – Sustainable Built Environment, III*, 249–256.

Tiemo, A. P., & Ofua, J. O. (2010). Technostress: Causes, Symptoms and Coping Strategies among Librarians in University Libraries. *Educational Research*, *1*(12), 713-720.

Trenca, C. A., Koenig, J. Q., & Williams, P. V. (2001). Dietary antioxidants and ozone-induced bronchial hyperresponsiveness in adults with asthma.*Archives of Environmental Health: An International Journal*, *56*(3), 242-249.

Torpy, F. R., Irga, P. J., Moldovan, D., Tarran, J., and Burchett, M. D. (2013). Characterization and Biostimulation of benzene biodegradation in the potting-mix of indoor plants. *Journal of Applied Horticultur*e, 15(1), 10–15.

Treesubsuntorn, C., & Thiravetyan, P. (2012). Removal of benzene from indoor air by Dracaena sanderiana: Effect of wax and stomata. *Atmospheric Environment*, 57, 317–321.

Tseng, Y. C., Lee, D. S., Lin, C. F., & Chang, C. Y. (2013). A Novel Sensor Platform Matching the Improved Version of IPMVP Option C for Measuring Energy Savings. *Sensors*, 13, 6811– 6831.

Ugrekhelidze, D., Korte, F., and Kvesitadze, G. (1997). Uptake and transformation of benzene and toluene by plant leaves. *Ecotoxicology and Environmental Safety*, 37, 24–29.

Uhde, E., & Salthammer, T. (2007). Impact of reaction products from building materials and furnishings on indoor air quality—a review of recent advances in indoor chemistry. *Atmospheric Environment*, *41*(15), 3111-3128.

Vanderzanden, A. M. (n.d.). Botany Basics. In J. Moore (Ed.), *Botanical Basics*. Retrieved from VanDerZanden, A. M. Botany Basics.

Varini, C. (2013). ECOENVELOPES R&D. Passive architectural envelopes high thermal performance and low environmental impact for tropical geo-climatic zones. *Informes de La Construcción*, 65(Extra-1), 23–30.

Vazquez, K. and Adams, L. (2014). The Level of Volatile Organic Compounds Exposure in New Buildings : Can Adding Indoor Potted Plants Reduce Exposure ? Kelly Vazquez and Lydia Adams College of Nursing The

University of Alabama in Huntsville. *In Proceedings of the National Conference on Undergraduate Research (NCUR*), 531–540.

Vuokko, A., Selinheimo, S., Sainio, M., Suojalehto, H., Järnefelt, H., Virtanen, M., ... & Karvala, K. (2015). Decreased work ability associated to indoor air problems–An intervention (RCT) to promote health behavior. *Neurotoxicology*, 49, 59-67.

Walz, K. (2012). Stress related issues due to too much technology: Effects on working professionals.

Wang, Y., Bakker, F., de Groot, R., & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment*, 77(0), 88–100.

Wang, Z. (2011). Dynamic Botanical Filtration System for Indoor Air Purification. Syracuse University. A PhD Dissertation

Wang, Z., Pei, J., & Zhang, J. S. (2012). Modeling and simulation of an activated carbon-based botanical air filtration system for improving indoor air quality. *Building and Environment*, 54, 109–115.

Wang, Z., Pei, J., & Zhang, J. S. (2014). Experimental investigation of the formaldehyde removal mechanisms in a dynamic botanical filtration system for indoor air purification. *Journal of Hazardous Materials*, 280, 235–243.

Wang, Z., & Zhang, J. S. (2011). Characterization and performance evaluation of a full-scale activated carbon-based dynamic botanical air filtration system for improving indoor air quality. *Building and Environment,* 46(3), 758–768.

Ward, M., Siegel, J. A., & Corsi, R. L. (2005). The effectiveness of stand-alone air cleaners for shelter-in-place. *Indoor Air*, *15*(2), 127–134

Weber, G. F. (1973). *Bacterial and fungal diseases of plants in the tropics*. University of Florida Press.

Weng, P.-Y. and Chiang, Y.-C. (2014). Psychological Restoration through Indoor and Outdoor Leisure Activities. *Journal of Leisure Research*, 46(2), 203–217.

Wolverton, B. C., Johnson, A., & Bounds, K. (1989). Interior landscape plants for indoor air pollution abatement. *National Aeronautics and Space Administration* (NASA). USA.

Wolverton, B., & Wolverton, J. (1993). Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *Journal of the Mississippi Academy of Sciences,* 38, 11–15.

Wong, N. H., Kwang Tan, A. Y., Chen, Y., Sekar, K., Tan, P. Y., Chan, D., … Wong, N. C. (2010). Thermal evaluation of vertical greenery systems for building walls. *Building and Environment*, 45(3), 663–672.

Wong, N. H., Tan, A. Y. K., Tan, P. Y., & Wong, N. C. (2009). Energy simulation of vertical greenery systems. *Energy and Buildings*, 41(12), 1401–1408.

Wood, R. a., Burchett, M. D., Alquezar, R., Orwell, R. L., Tarran, J., Torpy, F., … Torpy, F. (2006). The potted-plant microcosm substantially reduces indoor air VOC pollution: II. Laboratory study. *Water, Air, and Soil Pollution*, 177, 59–80.

Xu, Z., Wang, L., & Hou, H. (2011). Formaldehyde removal by potted plant-soil systems. *Journal of Hazardous Materials*, 192(1), 314–318.

Xu, Z., Wu, M., & He, Y. (2013). Toluene biofiltration enhanced by ryegrass. *Bulletin of Environmental Contamination and Toxicolog*y, 90, 646–649.

Yang, D., Pennisi, S., Son, K., & Kays, S. (2009). Screening indoor plants for volatile organic pollutant removal efficiency. *HortScience*, 44(5), 1377–1381.

Yoo, M. H., Kwon, Y. J., Son, K., & Kays, S. J. (2006). Efficacy of indoor plants for the removal of single and mixed volatile organic pollutants and physiological effects of the volatiles on the plants. *Journal of the American Society for Horticultural Science*, 131(4), 452–458.

Zhang, J. (Jensen) S., & Wang, Z. (2010). *Air cleaning technologies for indoor air quality (ACTIAQ): Growing fresh and clean air NYSERDA's promise to New Yorkers*, New York State energy research and development authority (NYSERDA). Albany, NY.

Zhang, J., Wang, Z., & Ren, D. (2010). Myth and Facts: Botanical Air Filtration. *ASHRAE Journal*, 52(12), 138–140.

Zhang, Y., Mo, J., Li, Y., Sundell, J., Wargocki, P., Zhang, J., … Sun, Y. (2011). Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. *Atmospheric Environment*, *45*(26), 4329–4343

Zhou, J., Qin, F., Su, J., Liao, J., & Xu, H. (2011). Purification of formaldehyde-polluted air by indoor plants of *Araceae, Agavaceae* and *Liliaceae*. *Journal of Food, Agriculture & Environmen*t, 9(3–4), 1012–1018.

.

Appendices

Appendix 1: CADR for plants is calculated using the statistical method by linear regression model

The AHAM. ANSI/AHAM AC-1-2006 is a standard method for measuring performance of portable household electric room air cleaners. Theoretically, the regression of pollutant concentration follows a first-order decay model:

$$C_t = C_0 e^{-kt} \tag{1}$$

where C_t = concentration at time t [ppm], C_0 = initial concentration at t = 0 [ppm], k = decay constant [t^{-1}], and t = time [h].

For the case of graphical representation about the pollutant removal by indoor plants, the time-resolved decay constant k is calculated statistically using a linear regression of $\ln C_{t_i}$ and t_i using the following formula:

$$k = \left[\frac{S_{XY}}{S_{XX}}\right] \tag{2}$$

where

$$C_{t_i} = \frac{C_t}{C_0} \qquad \text{and} \qquad S_{XX} = \sum_{i=1}^{n} (t_i)^2 - \frac{1}{n} \left(\sum_{i=1}^{n} t_i\right)^2$$

$$S_{XY} = \sum_{i=1}^{n} t_i \ln C_{t_i} - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)\left(\sum_{i=1}^{n} \ln C_{t_i}\right)$$

For the case of graphical representation about the pollutant removal by indoor plants, the decay loss will be calculated by normal logarithmic of the normalized concentration $C_{t_i} = \frac{C_t}{C_0}$

$$k = \frac{-\ln\left(C_{t_i}\right)}{t} \tag{3}$$

Using Eqs. (1) and (2) or (3), the CADR is calculated as the following:

$$CADR = V_c \ (k_e\text{-}k_n) \tag{4}$$

where CADR = clear air delivery rate [m^3/h], V_c = volume of test chamber [m^3], k_e = total decay rate [h^{-1}], and k_n = natural decay rate [h^{-1}].

Appendix 2 Examples of Calculating CADR values

Some examples of calculating the CADR value from some articles are presented under two cases.

(a) For the case of numerical values only:

Example (1):

Mosaddegh et al. (2014) investigated the benzene removal by a plant species of *D. deremensis* and *O. microdasys.*

The initial toluene concentration is C_0 = 0.72 ppmv, the chamber volume is 0.05 m^3, and exposure time is at 100h. the results are the following:

(a) Without a plant inside a chamber:
C_t = 2 ppm, S_{xx} = 18200, S_{xy} = -132.648, K_n = -0.0073 h^{-1}

(b) Adding a plant inside the test chamber since the maximum decay rate for *O. microdasys*,

C_t = 2 ppmv, S_{xx} = 18200, S_{xy} = -1260.581, K_t = -0.0693h^{-1}

Therefore, the CADR value is 0.003 m^3/h.

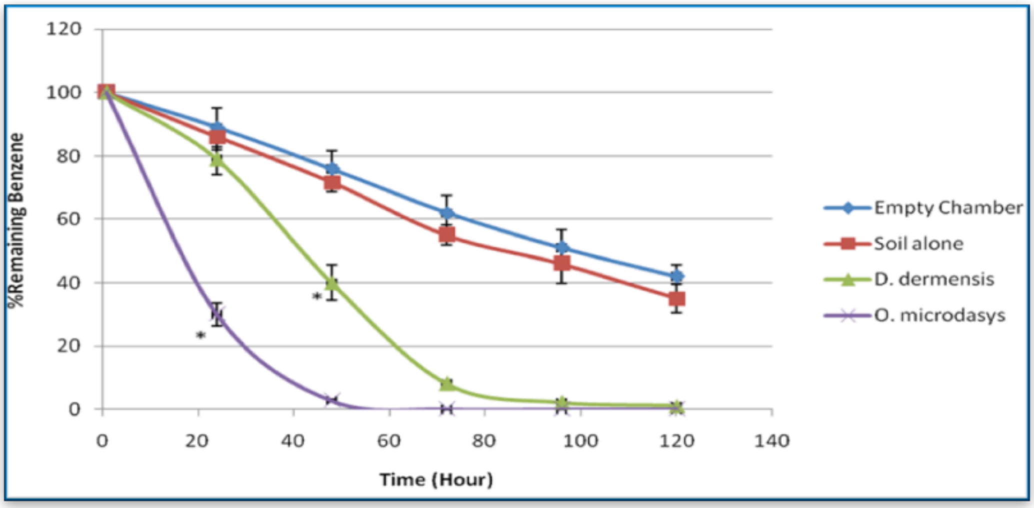

Figure 7. 1: The benzene concentration versus time copied from (Mosaddegh et al., 2014)

Example (2):

De kempeneer et al. (2004) investigated the toluene removal by a plant species of *Azalea indica* with repeated addition of toluene.

The initial toluene concentration is $C_0 = 100$ ppmv, the chamber volume is 0.023 m^3, and exposure time is at 100h. the results are the following:

(c) Without a plant inside a chamber $C_t = 80$ ppmv, $S_{xx} = 33915.184$, $S_{xy} = -55.160$, $K_n = -0.0016\ h^{-1}$

(d) Adding a plant inside the test chamber,

$C_t = 2$ ppmv, $S_{xx} = 33915.184$, $S_{xy} = -1266.733$, $K_t = -0.0374\ h^{-1}$.

Therefore, the CADR value is 0.0008 m^3/h.

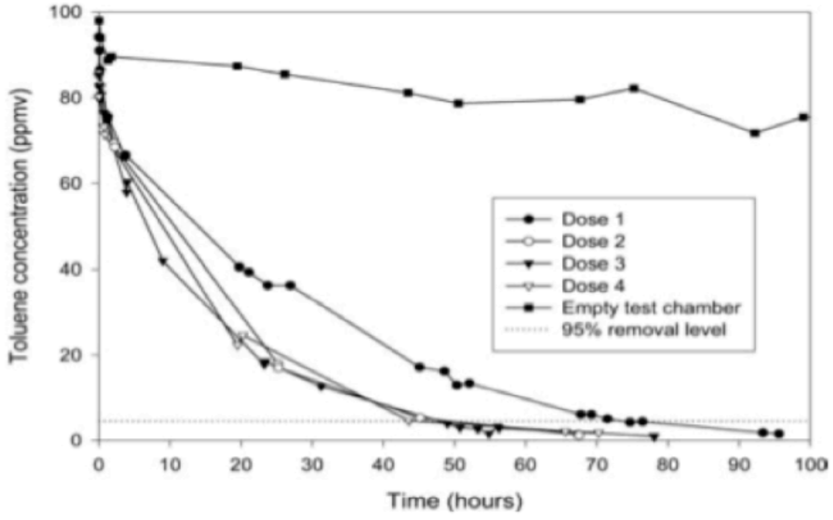

Fig. 1 Toluene removal by non-inoculated *Azalea indica* following repeated addition of toluene to the test chamber. Curves start at the time when toluene concentrations started to decline in the chamber (about 10 min after toluene addition). Other replicates resulted in similar curves

Figure 7. 2: The toluene concentration versus time copied from (De kempeneer et al., 2004)

(b) For the case of graphical representations of the pollutant loss.

Example (3):

Kim and Lee 2008 investigated the removal of formaldehyde by various plant species

Plant Species	Leaf Area (m^2/chamber)	Removal Rate [$\mu g.m^{-3}.mL^{-1}$]	C_o-C_t [mg/m^3]	Removal Efficiency [%]	C_0/C_t	k_t
Phalaenopsis spp.	0.48	0.62	2.05	83.5	6.06	0.90
Cymbidium spp.	5.25	0.14	0.54	22.1	1.28	0.12
Cymbidium Meglee	2.06	0.29	0.97	39.7	1.66	0.25
Oncidium spp.	0.53	0.54	0.83	33.8	1.51	0.21
Dendrobium phalaenopsis	0.58	0.62	1.83	74.6	3.94	0.69
Sansevieria trifasciata	2.86	0.23	0.71	28.9	1.41	0.17
Ficus benjamina	1.34	0.55	1.51	61.7	2.61	0.48

The chamber volume is $V_c = 0.9963\ m^3$, exposure time t = 5h, initial concentration $C_0 = 2.454\ mg/m^3$, and the natural decay rate $k_n = 0$ (no without plants investigation). The CADR value = 0.898 m^3/h based on maximum value of k_t-k_n = 0.90 h^{-1}.

Example (4):

Chun et al., 2010 investigated removal of several VOCs and a mixture of them with various plants species. The chamber test is glass bottle of a volume of $Vc = 0.0009\ m^3$.

(a) Benzene: $C_0 = 0.36\ \mu l.L^{-1}$

Plant species	C_t [$\mu l.L^{-1}$] at 1h	C_t [$\mu l.L^{-1}$] at 12h	η [%]	k_t [h^{-1}]	CADR [m^3/h]
Control	0.428	0.173	60.0	$k_n = 0.061$	----
S. trifasciata	0.39	0.121	69.1	0.091	8.0E-05
D. deremensis	0.451	0.138	69.5	0.080	7.0E-05
N. exalatata	0.553	0.167	69.7	0.064	5.6E-05
S. wallisii	0.403	0.105	74.1	0.103	9.0E-05
P. aquatic	0.633	0.114	82.0	0.096	8.4E-05
F. elastica	0.357	0.028	92.2	0.213	0.0001
S. aureus	0.229	0.071	69.0	0.135	0.0001
Dieffenbachia spp.	0.235	0.0001	99.9	0.682	0.0006
C. elegans	0.159	0.0001	99.9	0.682	0.0006

The natural decay rate is $k_n = 0.061$ h^{-1} and the total decay rate is $k_t = 0.682$ h^{-1}, the maximum CADR value is 0.0006 m^3/h.

(b) Toluene: $C_0 = 0.18$ μl.L^{-1}.

Plant species	**C_t [μl.L^{-1}] at 1h**	**C_t [μl.L^{-1}] at 12h**	**η [%]**	**k_t [h^{-1}]**	**CADR [m^3/h]**
Control	0.145	0.05	65.2	$k_n = 0.107$	----
S. trifasciata	0.209	0.035	83.5	0.136	0.0001
D. deremensis	0.315	0.03	90.6	0.149	0.0001
N. exalatata	0.355	0.0001	100.0	0.625	0.0005
S. wallisii	0.21	0.0001	100.0	0.625	0.0005
P. aquatic	0.482	0.077	83.9	0.071	6.2E-05
F. elastica	0.119	0.0001	100.0	0.625	0.0005
S. aureus	0.182	0.0001	80.9	0.625	0.0005
Dieffenbachia spp.	0.13	0.0001	100.0	0.625	0.0005
C. elegans	0.099	0.0001	100.0	0.625	0.0005

The natural decay rate is $k_n = 0.107$ h^{-1} and the total decay rate is $k_t = 0.625$ h^{-1}, the maximum CADR value is 0.0005 m^3/h.

(c) m,p-Xylene: $C_0 = 0.976$ μl.L^{-1}.

Plant species	**C_t [μl.L^{-1}] at 1h**	**C_t [μl.L^{-1}] at 12h**	**η [%]**	**k_t [h^{-1}]**	**CADR [m^3/h]**
Control	1.185	0.081	93.1	$k_n = 0.207$	----
S. trifasciata	1.006	0.052	94.8	0.244	0.0002
D. deremensis	1.89	0.055	97.1	0.240	0.0002
N. exalatata	2.291	0.186	91.9	0.138	0.0001
S. wallisii	1.174	0.026	97.8	0.302	0.0003
P. aquatic	4.253	0.013	99.7	0.360	0.0003
F. elastica	0.829	0.0001	100.0	0.766	0.0007
S. aureus	1.224	0.043	96.5	0.260	0.0002
Dieffenbachia spp.	0.798	0.0001	100.0	0.766	0.0007
C. elegans	0.558	0.0001	100.0	0.766	0.0008

The natural decay rate is $k_n = 0.207$ h^{-1} and the total decay rate is $k_t = 0.766$ h^{-1}, the maximum CADR value is 0.0008 m^3/h.

(d) o-xylene: $C_0 = 0.569$ μl.L^{-1}.

Plant species	**C_t [µl.L^{-1}] at 1h**	**C_t [µl.L^{-1}] at 12h**	**η [%]**	**k_t [h^{-1}]**	**CADR [m^3/h]**
Control	0.61	0.0001	100.0	$k_n = 0.721$	----
S. trifasciata	0.491	0.0001	100.0	0.721	0.0006
D. deremensis	0.984	0.009	99.0	0.346	0.0003
N. exalatata	1.22	0.025	98.0	0.260	0.0002
S. wallisii	0.557	0.0001	100.0	0.721	0.0006
P. aquatic	2.513	0.0001	100.0	0.721	0.0006
F. elastica	0.438	0.0001	100.0	0.721	0.0006
S. aureus	0.625	0.0001	100.0	0.721	0.0006
Dieffenbachia spp.	0.408	0.0001	100.0	0.721	0.0006
C. elegans	0.251	0.0001	100.0	0.721	0.0006

The natural decay rate is $k_n = 0.721$ h^{-1} and the total decay rate is $k_t = 0.721$ h^{-1}, the maximum CADR value is 0.0006 m^3/h.

(e) Total mixture: $C_0 = 2.085$ µl.L^{-1}.

Plant species	**C_t [µl.L^{-1}] at 1h**	**C_t [µl.L^{-1}] at 12h**	**η [%]**	**k_t [h^{-1}]**	**CADR [m^3/h]**
Control	2.099	0.285	0.864	$k_n = 0.166$	----
S. trifasciata	2.096	0.208	0.901	0.192	0.0002
D. deremensis	3.64	0.232	0.936	0.183	0.0002
N. exalatata	4.419	0.378	0.914	0.142	0.0001
S. wallisii	2.344	0.131	0.944	0.231	0.0002
P. aquatic	7.788	0.204	0.974	0.194	0.0002
F. elastica	1.788	0.028	0.984	0.359	0.0003
S. aureus	2.26	0.149	0.934	0.220	0.0002
Dieffenbachia spp.	1.571	0.0001	1	0.829	0.0007
C. elegans	1.067	0.0001	1	0.829	0.0007

The natural decay rate is $k_n = 0.166$ h^{-1} and the total decay rate is $k_t = 0.829$ h^{-1}, the maximum CADR value is 0.0007 m^3/h.

Example (5):

Newkirk et al., 2014 investigated the toluene removal by a biowall in a test chamber. The initial concentration $C_0 = 200$ ppm, exposure time $t = 5$ h inside a chamber test of $V_c = 0.072$ m^3. The natural decay rate for without biowall is $k_n = 0.043$ h^{-1}, and the total decay rate for with biowall $k_t = 0.120$ h^{-1}. Therefore, the CADR value is 0.006 m^3/h.

Copyright Acknowledgements

How I thank people before I thank my Lord who created the people who help me and created everything in the universe. I am so grateful to Allah who let the destiny chose me and my husband to travel to Canada and pursue our graduate studies. The first verse that revealed to Prophet Mohamed (PBUH) was Read-Read-Read. The Muslim Ummah are suffering from illiteracy and tyranny, and it is my duty to travel far away from my family and my country to gain knowledge to assist the Muslim Ummah. My hope is to benefit the Muslim Ummah and other interested nations with my master thesis.

I am so grateful to Allah who let Prof. Jeffrey Siegel to be my supervisor. He is a brilliant researcher and a professional writer. He also was and still patient, supportive, and advisor through my challenges in research and writing during my journey of master thesis. I will be not grateful if I don't mention the staff of the University of Toronto during their collaboration in my administrative work. Also, the instructors and professors of my courses are thankful for helping me in comprehending the course materials. In addition, the colleagues in my research team are thankful for their support and their pleasurable time.

A great thanking to my supportive and beloved husband Amro Ibrahim by providing a good studying environment and taking care of our children. In addition, recognizes to my parents who prayed for me during my challenges.

Thanks to All!