The impact of plants on indoor air quality and the wellbeing of building occupants

Doctor of Philosophy

School of the Built Environment

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February 2023

DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

………………………………………………………………

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November 2022

Abstract

Indoor plants are introduced into buildings to benefit the occupants' health and well-being, but their room-scale impact and effect on people's responses is poorly understood. Through experiments in controlled chambers, naturally ventilated offices and measurements of people's psychological responses, this thesis investigated interactions between the plant, indoor air quality (IAQ) and building occupants.

There were significant differences between the plants' performance in chamber-scale versus room-scale experiments. Species selection, leaf area and planting density were identified as key factors for maximising [CO_2] reduction and adding moisture to indoor environments. Most moisture was added by plants in hot, dry environments. At office-scale, the building design, air change rate (ACH) and environmental conditions had a greater impact than the plants on the rate of CO_2 and moisture removal from the office ($28m^3$). There was a seasonal variation in the ACH and the plants' evapotranspiration rate, with the highest rates in the summer. In the offices the plants emitted 35-68 g of water vapour/day/plant depending on the species and environmental conditions, but 65% -100% was lost through air exchange and absorption. No significant impact on the [CO_2] reduction rate was determined.

Whilst the impact of potted plants on IAQ was small or insignificant at office-scale, the physical appearance of the plant had a significant impact on 520 participants, whose responses were measured through a photo-questionnaire. All healthy plants were perceived to positively impact wellbeing and IAQ. An unhealthy plant was perceived negatively for wellbeing and IAQ impacts. Perceptions of wellbeing benefits were affected by the participants' perceived interest and beauty of the plant. Perceived IAQ benefits were associated with the healthiness of the plant appearance and canopy density. Participants perceived the plants would have a greater benefit for their well-being than for IAQ.

Acknowledgements

First and foremost I would like to thank my supervisors Dr. Emmanuel Essah and Dr. Tijana Blanusa for their guidance, support, positivity and constant encouragement over the past four years.

Thankyou also to Professor Phil Beaman for his invaluable help with the psychology studies.

I would also like to thank all glasshouse staff at the University of Reading, especially Val Jasper, Liam Doherty and James Hadley and to the staff of the RHS for their help and advice with the plant experiments and maintenance.

My thanks to all of the past students of the TSBE Centre who have achieved so much and inspired me undertake this research, and to the staff in the School of the Built Environment for their support.

Thank you to my great friends for keeping me sane and for their constant encouragement.

Finally, thank you to my family who have shared every step of this journey - to James for his calm, wit and wisdom - to Dr. Zoe Berger, my truly amazing study buddy who led the way and to Steve - without whom this would not have been possible.

Dissemination of the Research Findings

Journal Publications

Berger et al., 2022. The appearance of indoor plants and their effect on people's perceptions of indoor air quality and subjective well-being. *Building and Environment*, *219*, p.109-151.

Conference presentations

“The Impact of Plants on Indoor Environments”
SBE, University of Reading PhD Conference, 2020
Abstract and presentation

“The Impact of Plants on Indoor Air Quality and People’s Wellbeing”
Ambius, National UK Conference, 2020
Presentation

"The Impact Of Plants On Indoor Air Quality”
Royal Horticultural Society, PhD Conference, 2019
Abstract and presentation

“Greening the Indoor Environment”
Chongqing University Summer School, held at the University of Reading, 2019
Lecture to M.Sc. students

“The Impact of Plants on Indoor Air Quality”
SBE, University of Reading PhD Conference, 2019
Conference poster presentation and Presentation

“The interaction of plants with the environmental quality of the building”
BSRIA, Engineering Wellbeing in the workplace, National conference, 2018
Abstract and presentation

Public dissemination

Radio Berkshire 19 June 2022 – The Gardening Show. The impact of the appearance of indoor plants on people's perceptions of indoor air quality and subjective wellbeing

Breakfast TV New Zealand. June 2022. The impact of the appearance of indoor plants on people's perceptions of indoor air quality and subjective wellbeing

RHS Podcast August2022 – Gardening with the RHS. Indoor plants and wellbeing.

Press coverage in the UK national papers June 2022. The impact of the appearance of indoor plants –featured in The Telegraph, The Guardian, The Independent, and lifestyle magazines.

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Abbreviations

ACH	Air change rate
AER	Air exchange rate
AH	Absolute humidity
ANOVA	Analysis of variance
ASHRAE	The American society of heating, refrigeration and air-conditioning engineers
ART	Attention Restoration Theory
BSRIA	Building Services Research and Information Association
CADR	Clean air delivery rate
CAM	Crassulacean Acid Metabolism
CIBSE	Chartered institution of building services engineers
CO_2	Carbon dioxide
CO	Carbon monoxide
DF	Degrees of freedom
ET	Evapotranspiration
HVAC	Heating, ventilation and air conditioning system
IAQ	Indoor air quality
IEQ	Indoor environmental quality
IRGA	Infra-red gas analyser
LA	Leaf area
LAD	Leaf area density
LCP	Light compensation point
MANOVA	Multivariate analysis of variance
LEED	Leadership in Energy and Environmental Design
NOx	Nitrogen oxides
O_2	Oxygen
PAR	Photosynthetically active radiation (µmol m^{-2} s^{-1})
PM	Particulate matter
$PM_{2.5}$	PM with a diameter less than or equal to 2.5 µm
PM_{10}	PM with a diameter less than or equal to 10 µm
ppm	Parts per million

RH	Relative humidity
RHS	Royal Horticultural Society
SBS	Sick building syndrome
SBW	Subjective wellbeing
SD	Standard deviation
SEM	Standard error of the mean
SMC	Substrate moisture content ($m^3\,m^{-3}$)
SRT	Stress Reduction Theory
T_a	Air temperature (°C)
VOCs	Volatile organic compounds
VPD	Vapour pressure deficit (kPa)

Chapter 1

Introduction and literature review

1.1 Introduction

In 1943, Sir Winston Churchill said, **“*We shape our buildings; thereafter they shape us.*”** (Churchill Winston, 1943). Today, buildings continue to have a major impact on our daily lives.

People now spend up to 90% of their time indoors (Klepeis et al., 2001), and the quality of the indoor environment has a significant impact on the health, comfort, productivity, satisfaction and wellbeing of building occupants. Staff costs typically account for 90% of business operating costs and in the USA; it was estimated that annual savings from health and productivity gains, of $37-208 billion, could be achieved by improving the indoor environmental quality (IEQ) (Fisk, 2000). In the UK around one third of employees work in office type of environments and it is estimated that IEQ improvements could lead productivity gains of 3-15% (Clements-Croome, 2006).

The supply of fresh clean air is vital for human survival and indoor air quality (IAQ) is a major contributor to the overall quality of the indoor environment. Since the times of Hippocrates and the Romans, there has been an awareness that polluted air can adversely affect human health, but currently in the UK poor air quality is responsible for 3 million lost working days per year at a cost of approximately £600m annually (CBI-Economics, 2020). As people spend increasing amounts of time indoors the concerns about IAQ are rising but to maintain good IAQ with mechanical ventilation systems is energy intensive. In 2020, energy use for the construction and operation of buildings were responsible for 36 per cent of global energy demand and 37 per cent of energy-related CO_2 emissions (UN Environment Programme, 2021). It is estimated that heating, ventilation and air conditioning systems, consume up to 40% of the energy used in office buildings in the European Union (Chenari et al., 2016; Luengas et al., 2015). To mitigate the negative impacts of climate change and rapidly rising energy costs, there is an urgent need to cut emissions, reduce energy demand and to find alternative sustainable, low energy methods for improving IAQ. Indoor plants have the potential to improve the IAQ, but studies are needed to quantify their impact in real-world environments.

A further major health concern is the rapidly increasing rise in mental illness, which is now the second-largest source of burden of disease in UK. Stress, depression and anxiety accounted for 55% of all working days lost due to work-related ill health in 2019/20 at an estimated cost of £35 billion (Health and Safety Executive, 2020). Thus, even small improvements in the mental wellbeing of occupants can lead to significant increases in productivity and financial gains. The psychological wellbeing of a person depends on many factors but the indoor environment, including the physical design of the space is an important influence which can be manipulated in various ways (Clements-Croome, Turner, & Pallaris, 2019). The addition of indoor plants impacts the visual design of the indoor built environment and can benefit the psychological wellbeing of building occupants, but it is not known how people respond to the physical appearance of different plants.

These issues form the background to the need for this research.

1.2 The literature review

This literature review sets the scene for understanding the importance of the quality of the indoor environment within buildings and the impact that indoor plants can have for the benefit of the health, comfort and wellbeing of occupants. The first part of the review considers the problems with IEQ within office environments and the role that plants can play in improving this. The second part reviews the impact that plants can have on the psychological wellbeing and productivity of office workers. After critically reviewing the existing literature, the conclusions pull together the knowledge gaps where a future contribution to the literature can be made. Each chapter includes a short review of the relevant key literature to present the work in a publishable format and to facilitate readers who prefer to read the chapters in isolation.

1.2.1 Indoor environmental quality and its importance for building occupants

Several large-scale studies have investigated the health, comfort and complaints of thousands of office workers in the USA (Brightman et al., 2008), Europe (de Kluizenaar et al., 2016; Bluyssen, Aries, & van Dommelen, 2011; Bluyssen et al., 1996) and the UK (Marmot & Wilkinson, 2006).
One of the earliest studies, the European Indoor Air Quality Project 1992, included physical and chemical measurements of the IAQ of 56 offices across Europe and assessment of the perceived air quality, health symptoms and thermal comfort from building occupants (Bluyssen et al., 1996). All of the office buildings were perceived as having dry air and the highest number of complaints were dry skin, lethargy, headaches, dry eyes, dry throat, and a stuffy nose. Despite good ventilation rates (average of 25 L s^{-1} $person^{-1}$) and pollutant concentrations meeting national standards, 30% of the occupants and 50% of the visitors found the air unacceptable. Although higher ventilation rates corelated with better perceived air quality, it was concluded that the main

source of pollution was the building itself and the ventilation system, rather than the occupants (Bluyssen et al., 1996). Only 12% of the buildings were naturally ventilated and it is not known if the IAQ was better in these buildings. The study was only conducted during the heating season, and smoking was permitted in buildings which can have a significant negative impact on IAQ, and large sources of uncertainty were associated with ventilation measurements and in calculating pollutant loads.

The USA Building Assessment Survey and Evaluation (BASE) 1994-1998, measured determinants of IAQ and occupant perceptions in 100, randomly selected office buildings (U.S. Environmental Protection Agency, 2003). Factor analysis on over 4000 occupant responses identified four main groups of symptoms: tiredness, mucosal irritation, neuropsychological and lower respiratory conditions. At least one work-related symptom was reported by of 45% of the work force and three symptoms by 20% of the workforce (Brightman et al., 2008). A second study of ‘complaint’ buildings, confirmed the same rank ordering of prevalence of symptoms: eye symptoms, tiredness, headaches, neck pain, stuffy nose, dry/sore throat and lastly breath/wheezing (Brightman et al., 2008). A follow-on study of 98 workers, in four office buildings, showed eye irritation was positively correlated with floor dust, and carbon dioxide (CO_2) concentration with upper respiratory symptoms (Chao et al. 2003). Dry skin complaints were lower in the USA studies than in the earlier European study, highlighting that whilst the main symptoms occur consistently, the prevalence of symptoms can be building specific.

The European Health Optimization Protocol for Energy efficient buildings (HOPE) 2002-2005, aimed to provide the means for the construction industry to increase the number of energy-efficient, healthy buildings (Bluyssen, 2002). Building inspections and responses from nearly 6000 office workers, showed perceived occupant health was generally correlated with IEQ. Problems in the “less healthy” office buildings were associated with poor ventilation, high temperatures and high concentrations of particulate matter (PM). Poor ventilation occurred in both mechanically ventilated and naturally ventilated buildings (Bluyssen, Aries, & van Dommelen, 2011; Aizlewood & Dimitroulopoulou, 2006). Lighting, noise, temperature, IAQ and the office environment, including decoration strongly affected perceived comfort (Bluyssen, Aries, & van Dommelen, 2011). The findings varied between countries, some differences could be explained by the different buildings, but perceived occupant comfort and satisfaction were also strongly influenced by other factors such as personal control, view, stress and work culture (Bluyssen, Aries, & van Dommelen, 2011; Aizlewood & Dimitroulopoulou, 2006). The strength of this study was the large number of respondents and buildings, but the occupants’ perceptions can’t be directly correlated with specific aspects of the IEQ as physical measurements and occupant's responses were not made at the same time.

Over 7000 respondents from the European project OFFICAIR (2011-2012), assessed their perceptions of the environmental conditions using two 7-point (unipolar or bipolar) Likert scales and their health responses with the Building Symptom Index (Bluyssen et al., 2016). The main complaints about overall comfort were noise, dry air, and temperature. Almost one third of office workers suffered from dry eyes and headaches over a 4 week period and 29% perceived their productivity was impacted by IEQ factors (Bluyssen et al., 2016). Portable humidifiers were identified as one of the factors associated with increased self-reported dry eye symptoms (de Kluizenaar et al., 2016), highlighting an important issue for modern offices; dry air is one of the main IEQ issues but the use of humidifiers can worsen the symptoms. Only 5% of buildings were naturally ventilated, but other studies have shown there is little difference in the occupant's satisfaction with the indoor environment, despite a greater variation in air temperature (T_a), relative humidity (RH) and CO_2 concentration in naturally ventilated offices compared to mechanically ventilated ones (Rasheed & Byrd, 2018; Hummelgaard et al., 2007).

In response to the issues posed by the energy crisis and climate change the introduction of the first green building rating first schemes in the 1990s were a major step change in the construction process, setting best practice standards for the environmental performance of buildings (Licina et al., 2021; Doan et al., 2017). Credits can be attained in some schemes for the inclusion of indoor plants (Green Star, 2022; LEED, 2022). Multiple schemes now exist worldwide and recent developments include ones which focus mainly on the benefit of the occupants (Fitwel, 2016; WELL, 2014). Generally green buildings are associated with increased employee wellbeing (Al horr et al., 2016) and perceptions of good IAQ (Lee et al., 2018; Steinemann, Wargocki, & Rismanchi, 2017) however, numerous field studies have identified occupant satisfaction with IEQ, including dry eye symptoms, remains an issue for both green-certified and non-green certified buildings (Lee et al., 2018; MacNaughton et al., 2017; Tham, Wargocki, & Fen Tan, 2015; Altomonte & Schiavon, 2013; Rae, Kerr, & Lee, 2011; Lee & Kim, 2008; Abbaszadeh et al., 2006). A study of five LEED certified buildings and five high performing non-certified buildings showed the RH was below 50% in both sets of buildings, but the air within the certified buildings was drier (RH 38.4% vs. 45.9%) (MacNaughton et al., 2017).

1.2.2 Definitions of IEQ, IAQ and thermal comfort

The indoor environment has many components which determine the IEQ. There are no universal standards for IEQ or IAQ but the American Society of Heating and Refrigerating and Air-Conditioning Engineers' (ASHRAE) provide a useful definition of IEQ parameters which includes: IAQ, thermal comfort, acoustics and lighting (ASHRAE, 2017)

IAQ is arguably the main component of IEQ and is defined by AHSRAE as: "*attributes of the respirable air inside a building (indoor climate), including gaseous composition, humidity, temperature, and contaminants*" (ASHRAE, 2013), and although alternative descriptions exist, the ASHRAE definition will be used in this study.

Thermal comfort is also a key parameter which affects occupants' wellbeing, productivity and satisfaction with the indoor environment (Geng et al., 2017; Clements-Croome, 2006). ASHRAE have defined thermal comfort as *"the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation"* (ASHRAE, 2017). Although difficult to quantify, it is determined by the relationship between the T_a, RH, air movement and the occupants' metabolic rate and clothing insulation value (HEVAC, 2016; Yao, Li, & Liu, 2009).

Other authors have argued that a broader approach to IEQ is needed, Bluyssen (2014) proposes that an integrative multi-disciplinary approach should be taken to provide a more human-focussed view of IEQ of how and why people respond to different environmental parameters. From a review of over 300 papers, identified eight physical factors of IEQ that affect occupant satisfaction and productivity in an office environment: indoor air quality; thermal comfort; office layout; noise; lighting; biophilia and views; aesthetics and location/amenities (Al Horr et al., 2016).

It is clear from all the studies that the relationship between IEQ factors and occupants' health and perceived satisfaction is complex, with many contributing factors including psychosocial ones.

1.2.3 Indoor air quality and pollutants

Indoor air is a complex mixture of compounds which are constantly changing as chemicals and particles change state and interact to form new compounds. A range of pollutants, broadly categorised as gases, vapours and particulate matter (PM) are the main cause of IAQ problems (Molhave, 2003). Indoor pollutants can enter the building from outside or be generated inside; risk from any single pollutant depends on the quantity that is emitted, the time period over which it is emitted and how hazardous the pollutant is (CIBSE, 2011).

The many negative health impacts caused by different indoor air pollutants have been widely studied and are summarised in Table 1.

Pollutant	**Sources**	**Health Impact**
Carbon monoxide (CO)	Combustion appliances	Headache, dizziness, nausea, unconsciousness, suffocation (CIBSE, 2011)
Carbon dioxide (CO$_2$)	Occupants during respiration Combustion appliances	Headaches, Narcotic, drowsiness, headaches, unconsciousness, nausea, fatigue (CIBSE, 2011; Seppanen, Fisk, & Mendell, 1999)
Human bioeffluents: Ammonia, hydrocarbons, alcohols, ketones, aldehydes	Occupants	Sick building syndrome Allergies (Redlich, Sparer, & Cullen, 1997)
Volatile Organic Compounds (VOCs)	Paints, resins, solvents, inks Printer and photocopier emissions Cleaning agents Building and furnishing materials Combustion and tobacco smoke (Hess-Kosa, 2011)	Sick building syndrome Cancer, Allergies Skin and throat irritation (Wolkoff, 2013; Fang et al., 2004; Molhave, 2003; Redlich, Sparer, & Cullen, 1997)
Particulates and fibres (non-biological)	Dust, asbestos, man-made mineral fibres (fibreglass), clothing fibres, dirt, construction, paper dust Printer and copier inks (He, Morawska, & Taplin, 2007)	Aggravation of cardiovascular and respiratory diseases (asthma, COPD*), allergic reactions, ultrafine particles can also enter the bloodstream to impact other organs such as liver, kidney and brain (Xing et al., 2016; Fisk, 2013)
Particulates (biological)	Human skin cells and hair Fungal spores, moulds, pollen Insects and dust mites Animal dander and excreta Viruses and bacteria (Hess-Kosa, 2011)	
Nitric oxide and Nitrogen dioxide (NOx)	Vehicle exhaust Industrial exhaust	Lung irritant, cancer (CIBSE, 2011; Brunekreef & Holgate, 2002)
Radon	Building materials, soil, igneous rocks	Lung irritant, cancer (CIBSE, 2011)
Ozone	Electrical equipment, UV light sources Due by action of sunlight on NOx	Ling irritant (CIBSE, 2011; Brunekreef & Holgate, 2002)

**COPD – Chronic obstructive pulmonary disease,*

Table 1.1: Sources of indoor air pollutants and their health impacts

The term Sick building syndrome (SBS) was originally used by the World Health Organisation (WHO) to describe a collection of non-specific health complaints from building occupants (HSE, 2000; WHO, 1983). Decades of research have shown it is a multi-factorial problem, which could be attributed to multiple causes, physical and social factors, and the current focus is on identifying the specific symptoms, their causes and effects (Carrer & Wolkoff, 2018; Wolkoff, 2013; Brightman et al., 2008).

From Table 1, the pollutants associated with the main complaints about IAQ and health issues in office environments identified in section 1.1 are; CO_2, PM and VOCs. Moisture is not included in the table and is discussed in 1.2.3.4.

1.2.3.1 Volatile Organic Compounds (VOCs)

VOCs are a group of organic compounds with boiling points from 50 to 100°C up to 240–260°C (Molhave, 2003; UK Government). Since the 1980s research has shown they can contribute to poor IAQ and increased health complaints such as SBS, in office environments (Wolkoff, 2013; Molhave, 2003). The role of indoor plants for potential VOC removal is an important area which has been widely researched but the studies have also shown that due partly to the very small quantities involved, accurate detection and measurement is difficult and specialist equipment is required (Gubb, 2020; Pettit, Irga, & Torpy, 2019; Treesubsuntorn & Thiravetyan, 2018; Choi, Park, Jung, J Lee, et al., 2016; Irga, Torpy, & Burchett, 2013; Aydogan & Montoya, 2011; Kim et al., 2010; Wood et al., 2002).

1.2.3.2 Particulates

Particulate matter (PM) is a complex mixture of solid or liquid phase particles suspended in the air. PM composition varies depending on the source of emissions, weather conditions, local and regional environments and temporal variations (Ansari & Ehrampoush, 2019). Particles with a diameter less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$) are of concern as these can be inhaled deep into the lungs or respiratory system (Harrison et al., 2010). Higher concentrations can be found indoors compared to outdoors, and these have been associated with increased reports of work-related health issues such as eye and respiratory symptoms (Lappalainen et al., 2013; Morawska et al., 2013). Numerous studies have identified the potential for plants to reduce indoor PM concentrations but these have also shown that indoor PM concentrations are difficult to measure accurately and it is difficult to isolate the effect of PM on its own due to its association with other characteristics of poor IAQ in particular RH (Pettit, Irga, & Torpy, 2019; Panyametheekul, Rattanapun, & Ongwandee, 2018; Wolkoff, 2018a; Gawrońska & Bakera, 2015; Schneider et al., 2003).

1.2.3.3 Carbon dioxide

One of the most common gaseous pollutants found inside buildings is carbon dioxide, a colourless gas at room temperature which is naturally present in the outdoor air at approximately 400 ppm (0.04%) (World Meteorological Organziation, 2017). It is estimated that, an average office worker generates around 0.0052 L s^{-1} (18.72 L h^{-1}) of CO_2 as a natural product of respiration, which causes indoor concentrations to increase in accordance with occupancy, activity levels and ventilation rates (Persily & de Jonge, 2017; Zhang, Wargocki, & Lian, 2017; Ng et al., 2012).

Whilst severe health effects are only experienced after exposure to extremely high concentrations (above 6,500 ppm) (Persily & de Jonge, 2017) studies have shown that exposure to CO_2 at concentrations below 5000 ppm, can increase health symptoms such as headaches, fatigue, eye or mucous membrane irritation, sore throat, and breathing problems (Jafari et al., 2015; Erdmann & Apte, 2004; Seppanen, Fisk, & Mendell, 1999). The UK Health and Safety Executive (HSE) have set a maximum exposure limit for CO_2 in the workplace of 5000 ppm (9150 mg m^{-3}) over 8 hours (Health and Safety Executive, 2018). Indoor CO_2 concentrations are typically used as a proxy for IAQ in buildings and the adequacy of ventilation (Wargocki et al., 2000; Wang et al., 2014; Allen *et al.*, 2016). Best practice industry guidance recommends a ventilation rate of 10 L s^{-1} per person or maintenance of a maximum indoor CO_2 concentration of approximately 1000 ppm (ASHRAE, 2013; CIBSE, 2006a, 2011).

A further consideration for office workers, is that even slightly increased CO_2 concentrations are associated with reduced cognitive performance and productivity (Fisk, 2000; Wargock et al., 2000; Mendell and Heath, 2005; Seppänen and Fisk, 2006). In a simulated office environment, participants' decision-making performance deteriorated progressively as the concentration of pure CO_2 was increased from 600ppm, to 1000ppm and then 2500 ppm (Satish et al., 2012). A later study by Allen et al.(2016), showed that even relatively small increases in CO_2 from 600 to 1000 ppm resulted in a 21% decrease in cognitive performance of 24 professional-grade employees in environmentally controlled experimental offices. An alternative study, which used different psychological tests and office tasks, found that cognitive performance was only affected at CO_2 concentrations above 3000 ppm (Zhang et al., 2017). The studies used different cognitive tests aimed at different groups of workers, which suggests that the impact of increasing CO_2 concentrations on cognitive performance in offices may vary with the task being undertaken; decision making tasks may be more significantly affected than routine office work.

Due to the importance of CO_2 for office IAQ and occupant wellbeing, and the high energy demands of maintaining CO_2 concentrations within acceptable limits, CO_2 was selected for this study.

1.2.3.4 Water vapour (moisture)

Dry indoor air (low RH), was identified as one of the most common complaints within office environments (section 1.1) (Wolkoff, 2018a; de Kluizenaar et al., 2016; Bluyssen et al., 1996, 2011). Clinical and office-based studies have shown that low RH (5-30%) can increase symptoms associated with dry eyes and drying of the mucous membranes (Wolkoff & Kjærgaard, 2007), reduced performance in office tasks (Wyon et al., 2006), higher absenteeism (Arundel et al., 1986) and possibly reduced work performance (Wolkoff, 2018a). Symptoms become more prevelant when the indoor heating is on and room temperatures rise above 22°C (Mizoue et al., 2004). Inhalation of dry air causes epithelial damage increasing susceptibility to ariborne infections (Moriyama, Hugentobler, & Iwasaki, 2020). Low RH has been associated with increased risk of COVID 19 (Nottmeyer & Sera, 2021) and higher transmission of the influenza virus (Lowen et al., 2007). Office environments with low humidity have also been associated with higher stress levels; a study in the USA of 134 office workers, showed a 25% lower stress response, and better sleep quality when participants spent the majority of their time in environments of 30-60% RH compared to drier environments (Razjouyan et al., 2020). Low humidity (below 40% RH) in office environments can also increase the problems associated with static electricity such as shocks, paper handling and damage to sensitive electronic equipment (CIBSE, 2006b; Nordstrom, Norback, & Akselsson, 1994).

The T_a and RH can have a significant impact on the perception of IAQ and thermal comfort of building occupants, both low and high humidity can be a problem and studies have shown perceived air quality decreases with increasing Ta and RH (Yao, Li, & Liu, 2009; De Dear, 2004; Fang, 1998; Toftum, Jørgensen, & Fanger, 1998; Berglund & Cain, 1989). Individual preferences vary and thermal comfort standards for indoor environments typically specify a range of recommended values of T_a and RH, these standards also determine the energy consumption by a building's environmental systems (Yao, Li, & Liu, 2009). Excessively high indoor humidity (above 70% RH for several days) is a serious concern within buildings due to the risk of condensation and mould growth, leading to a health risk for occupants and possible damage to the material condition of the building (Brambilla & Sangiorgio, 2020; Dedesko & Siegel, 2015; British Standards, 2011; World Health Organization, 2009).

For office work in the UK, the Health and Safety Executive (HSE) have set a legal minimum indoor temperature for safe working of 16 °C (Health and Safety Executive, 1992) but there is no legal standard for RH. Typical recommendations are to maintain indoor RH levels between 40-60% (British Standards, 2011; CIBSE, 2006a).

Due to the significant impact that high and low RH can have within indoor built environments, in addition to the energy demand and issues associated with air humidification, water vapour was selected for further investigation in this research.

1.2.4 Methods for improving the IAQ

To maintain an acceptable standard of IAQ and provide sufficient supply of fresh air, ventilation is typically used to dilute pollutant concentrations. Numerous methods of ventilation have been reviewed by Awbi (2017), which can be broadly categorised as natural, mechanical or mixed mode. Climatic forces such as wind, air pressure and temperature drive natural ventilation, whereas mechanical ventilation relies on electrically-driven fans and a network of ducts to distribute the fresh air (CIBSE, 2011; Awbi, 2003). Numerous studies have shown that increasing the rate of ventilation (> 10 L s^{-1}) is associated with significant decreases in symptoms of SBS and improvements of perceived air quality (Wolkoff, Azuma, & Carrer, 2021; Carrer et al., 2018; Wargocki et al., 2002; Seppanen, Fisk, & Mendell, 1999).

1.2.4.1 Air exchange and ventilation rates

Ventilation systems used in buildings typically rely on exchanging the polluted indoor air with fresh air from outside. The rate at which air enters and leaves a building is an essential parameter of ventilation and determinant of IAQ as it governs the speed of pollutant removal/dilution. The air change rate of a space is defined as the volumetric rate at which air enters (or leaves) a space divided by the volume of the space (Charlesworth, 1988), usually expressed in air changes per hour (ACH), where one ACH means that the total volume of air passing through an enclosed space in one hour is equal to the volume of that space.

The rate of air exchange can also be described as the air flow rate or ventilation rate, which is the volumetric amount of inflow air, per unit time (L s^{-1} or m^3 h^{-1}) (Carrer et al., 2018). In a UK office environment, the fresh air ventilation rate requirement is 10 L s^{-1} per person (CIBSE, 2011).

The relationship between ventilation rate and air-change rate is:

Ventilation rate (L s^{-1}) = Air change rate × Room volume (m^3) × 1000 (L m^{-3})/3600 (s h^{-1})

(Atkinson et al., 2009)

Mechanical ventilation systems can be energy intensive and poor maintenance can lead to inefficient operation and worsening of IAQ (Bluyssen, 2014). Natural ventilation systems often rely on features of the building such as windows or vents to enable air exchange, but when the outdoor air is cold, polluted or it is noisy, such ventilation openings remain closed and so the IAQ deteriorates. There is therefore an urgent need to find sustainable alternative methods to supplement existing systems for the improvement of IAQ.

1.2.5 The role of indoor plants in improving IAQ

Plant through photosynthesis and evapotranspiration (ET) have the potential to reduce CO_2 concentrations and add water vapour to the indoor air, these processes are discussed in 1.2.5.5.

1.2.5.1 The removal of CO_2 by indoor plants - Chamber scale studies

Many studies investigating the CO_2 removal potential of indoor plants of have been conducted in small-scale, sealed chambers where environmental parameters can more easily be controlled compared to real-world environments (Gubb et al., 2018; Treesubsuntorn & Thiravetyan, 2018; Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012; Oh, Jung, M. H. Seo, et al., 2011) .

The carbon sequestration of sixteen indoor plant taxa was evaluated in a study by Pennisi & van Iersel (2012), in growth chambers and an office environment. The carbon sequestration was determined from the increase in biomass of the plants over 10 weeks in the chambers and over 12 months in the office environment. All plants except *Sansevieria trifasciaita* 'Hahnii', *Dracaena* 'Janet Craig', *Dracaena* 'Lemon Lime' and *Dracaena marginata* increased the biomass and in the chambers, this increased with increasing light intensities of 10, 20 and 30 µmol m^{-2} s^{-1}, representative of the spectrum of indoor light intensities (500-2200 lx). In the office environment, woody plants and larger more mature plants, showed greater biomass increase than smaller herbaceous species and was influenced by the light intensity and size of container. This study measured the representation of the net carbon fixation by plants over a long time period, but it does not show what immediate, short-term impact the plants would have on CO_2 concentrations during the daytime when IAQ benefits are most needed for the benefit of occupants.

The impact of *Spathiphyllum clevelandii*, *Ficus benjamina*, and *Dypsis lutescens* on reducing, steadily increasing CO_2 concentrations, was investigated by Oh et al. (2011) who used hamsters inside sealed chambers (volume $0.5m^3$) to generate the CO_2. They showed that at a fixed light intensity of 1000 lux (approx. 15 µmol m^{-2} s^{-1}) all plants removed CO_2 (between 0.003-0.087 L CO_2 $plant^{-1}$ h^{-1}), and the removal rates increased with increasing CO_2 concentration up to the maximum 1000 ppm used in the experiments. Increasing the leaf area by using more plants within a chamber, had only a very small effect on the CO_2 removal rate, but this varied with plant species. The bioeffluents which would have been emitted by the hamsters alongside the CO_2 were not monitored and these may have affected the plants' performance.

Building on the work of the previous studies, Torpy, Irga, & Burchett (2014) investigated the impact of different light intensities and acclimatisation conditions on the CO_2 removal potential of eight indoor plant species. They used sealed chambers, added CO_2 from a cylinder and measured the change in concentration over 40 minutes to determine the removal rate. They determined the light response curves and light compensation points (LCP) for the plants. The results showed there were significant differences in the removal rates between species and their response to varying light intensities, ranging between removing 168 mg to adding 402 mg CO_2 $plant^{-1}$ h^{-1}. For most species, the LCPs were lower, and their CO_2 removal rates increased, when the plants were acclimatised under low light conditions compared to high light. The authors concluded that with targeted lighting indoor plants have the potential to reduce a small proportion of indoor CO_2 concentrations in real offices. Due to humidity build up in the chamber, the removal rates were measured over a short time, and it is not clear if the rates would be maintained over longer periods. The authors noted that in real-world environments other factors are likely to affect the results and this highlights a need for further field testing.

A further study by Torpy et al. (2017), investigated the reduction of CO_2 from a starting concentration of 1000 ppm by a green wall composed of *Chlorophytum comosum* and *Epipremnum aureum* within small-scale chambers and a sealed test room (volume $16m^3$) where the air leakage was accounted for. *Chlorophytum* had a higher CO_2 removal rate than *Epipremnum* and for both species the removal rates increased at higher light intensity and with the addition a fan although the results varied with species. The findings demonstrated the potential that indoor plants in well-lit rooms, can have for CO_2 reductions in such spaces but further field trials are needed to establish their impact in different types of real-world environments as the air flow and lighting can impact the results.

Another study demonstrated that growing edible salad plants, in sealed test cabins (264 m^3) generated sufficient oxygen (O_2) to satisfy the needs of 1.75 person per day and could absorb the CO_2 generated in a day by two people (Guo et al., 2014). The findings suggest there may be augmented benefits from growing edible plants indoors of IAQ improvements, but further investigation would be required to determine the impact within an office environment as the light intensity used (450-550 µmol m^{-2} s^{-1} or approx. 5000-6200 lux) was around 30-40 times higher than is found in a typical office. A nutrient solution growing medium was used which would have lower CO_2 emissions compared to conventional growing media. Another study compared the CO_2 and VOC removal capacity of *Syngonium podophyllum* plants over 40 minutes, grown in conventional potting mix or hydroculture in 15 L glass chambers (Irga, Torpy, & Burchett, 2013). The researchers found that at a light intensity of 10 µmol m^{-2} s^{-1} (approx. 460 lx) the plants grown in hydroculture removed 27% of the CO_2, whereas the potted mix plants increased the CO_2 concentration. When the light intensity was increased to 350 µmol m^{-2} s^{-1} the hydroculture plants reduced the CO_2 by 61%, compared to 37% for the plants grown in potted mix, showing that hydroculture may offer significant benefits for CO_2 removal by indoor plants compared to potting mix (Irga, Torpy, & Burchett, 2013; Wood et al., 2002).

A study by Gubb et al. (2018), developed the studies of CO_2 assimilation further by showing that the net CO_2 assimilation of seven common houseplants, decreased as the substrate moisture content decreased from >0.3 m^3 m^{-3} to <0.2 m^3 m^{-3}. All plants in their study emitted CO_2 at low light intensities (10 µmol m^{-2} s^{-1}). Substrate water deficiency appeared to have a smaller impact on the plants CO_2 removal capacity compared to light intensity, even though substrate moisture is known to induce stomatal closure and reduce ET rates. The LCPs measured in this study were higher than previous studies (Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) which suggests that the response to light intensity appears to vary with individual plants and experimental conditions. In this study the net CO_2 assimilation per plant was determined from leaf level measurements and this may not accurately represent the performance of the entire plant.

To overcome the problems of indoor light levels being too low for plant photosynthesis and net CO_2 removal by C3 plants, one study used a mixture of C3 and crassulacean acid metabolism (CAM) plants (refer to section 1.2.5.5.1 for more details on C3 and CAM plants) in a 15.6-L sealed glass chamber (Treesubsuntorn & Thiravetyan, 2018). They found that all studied plants emitted CO_2 at a light intensity of 50 µmol m^{-2} s^{-1}, but the results showing differences in CO_2 assimilation/emissions between C3 and CAM plants were inconclusive. The plants had a very small leaf area (130 cm^2) which would limit the capacity for CO_2 removal on a chamber scale and may indicate they were young plants, which were shown to have lower CO_2 assimilation potential in an earlier study (S.V. Pennisi & van Iersel, 2012). In addition, the LCPs of the plants weren't determined, and the light intensity may therefore have been insufficient for net CO_2 assimilation. Some plants such as *D. sanderiana* can display a facultative CAM pathway as an adaptation to stressed conditions (Jayasooriya et al., 2022) and it is therefore possible this may have happened in this study.

1.2.5.2 The removal of CO_2 by indoor plants - Room-scale studies

A small number of studies have investigated the CO_2 reduction of indoor plants at room-scale with varying results.

A study involving over 50 offices in Australia, either naturally ventilated or with air conditioning, reported mixed results in the reduction of CO_2 concentration, varying from no impact (Wood et al., 2006) to 10 - 25% reduction (Tarran, Torpy, & Burchett, 2007) after the addition of a range of plant species. A study in two large open plan offices in the UK, found no significant difference in the CO_2 concentrations between the office furnished with plants of a mixture of species, compared to the office without plants, where the CO_2 concentration was measured on a daily basis over a period of 6 months (Smith & Pitt, 2011). Neither of these studies took account of the impact of the ventilation system which was in operation, the outdoor CO_2 concentration and climate conditions, or the building occupants and their activities. In addition, daily or weekly samplings of the CO_2 were made which would only be representative of the IAQ at the point in time of the sampling. An office-based study in Thailand reported reductions of between 10-20% in the indoor daytime CO_2 concentration through the addition of varying numbers of *Sansevieria trifasciata* plants (Pamonpol, Areerob, & Prueksakorn, 2020), but as these are CAM plants, which assimilate CO_2 in the dark, the reductions are more likely to be due to other factors such as the ventilation, opening of doors and activities of the occupants.

In the above studies the CO_2 was generated by the occupants and ambient CO_2 concentrations were used. A study by Su & Lin (2015), used a sealed room, with no occupants and installed a green wall (5.72 m^2 area) composed of *Asplenium nidus* plants where substrate emissions were excluded by sealing the surface with foil. They added CO_2 to a concentration of 2000 ppm from a cylinder and found that the time taken for the CO_2 concentration to reduce to 800 ppm was approximately two hours faster (3h 50min compared to 5h 50min), in the room with the green wall compared to the room without plants, when a daytime lighting regime was used. The rate of reduction is likely to be slower when the surface of the growing medium is uncovered due to CO_2 emissions associated with the growing medium and plant root system. Although the room was sealed, the researchers did not account for the air infiltration which would have occurred, and further repeats of the experiment would be useful to determine if the findings are reproducible. Researchers in Austria, added CO_2 from a cylinder to a concentration of 2000ppm to two unoccupied comparable classrooms (Tudiwer & Korjenic, 2017). Over four repeats of the experiment, the CO_2 reduction was on average 3.5% faster in the classroom with a living wall containing *Epipremnum aureum* and *Davallia fejeensis,* compared to the classroom without plants. The researchers noted there was a fluctuation in the results over the repeated trials and that climatic factors may have had an effect and they surmised the majority of the CO_2 removal may have been due to air leakage.

1.2.5.3 Methods used for measuring the CO_2 reduction by plants

Most laboratory scale studies have been conducted in small (< $1m^3$) static, sealed chambers, sometimes with a small fan included to assist with air mixing (Gubb et al., 2018; Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; Irga, Torpy, & Burchett, 2013; Oh, Jung, M. H. Seo, et al., 2011; Fujii et al., 2005). CO_2 is injected to raise the concentration to between 1000 - 4000 ppm, after allowing the air to equilibrate, a sensor inside the chamber measures the change CO_2 concentration over time. To help control the T_a and RH inside the chamber the air can be circulated through a cooling and condensing system (Fujii et al., 2005), but this adds complexity and cost to the system and introduces a variable air flow, thus static chambers have been used in the majority of studies. Alternative methods include measuring the increase in biomass and growth and approximating the carbon assimilation (S.V. Pennisi & van Iersel, 2012) or measuring the change in CO_2 concentration at a leaf level using an Infrared Gas Analyser (IRGA) and estimating the plant level CO_2 reduction after deducting the CO_2 emissions from the substrate (Gubb et al., 2018).

In room-scale studies typically the change in CO_2 concentration over a given time has been measured. The starting CO_2 concentrations have ranged from ambient, often generated by the room occupants and therefore the concentrations are uncontrolled, or CO_2 has been added from a cylinder to concentrations typically up to 2000 ppm. The sampling of the CO_2 concentration has been conducted over different time periods, from continuous monitoring at 1-minute intervals to spot measurements on a weekly or monthly basis, although other studies have shown that spot, peak or average measurements of the CO_2 concentration or measurements including occupants are not reliable (Laussmann & Helm, 2004). Light intensity has varied from <10 µmol m^{-2} s^{-1}- to >450-550 µmol m^{-2} s^{-1} (<450 lx to >7000 lux).

In building ventilation studies, the concentration decay method using CO_2 as the tracer gas is a well-established method used to measure the change in CO_2 concentration over time and to determine air change rate of a room. Numerous studies summarise good practice techniques for field measurements of ventilation and IAQ (Persily, 2016; CIBSE, 2011; Persily & Levin, 2011; Laussmann & Helm, 2004; Awbi, 2003; Charlesworth, 1988). A one-time injection of CO_2 is added from a cylinder, the air is mixed for a brief time, and the change in CO_2 concentration over several hours is recorded by one or more sensors installed within the enclosed room, whilst all doors and windows are kept closed. Alternative methods include the constant emission and constant tracer gas injection methods, but these are more complex and used much less frequently (CIBSE, 2011; Awbi, 2003; Charlesworth, 1988).

1.2.5.4 Studies of the impact of plants on indoor humidity

Through evapotranspiration (ET) indoor plants potentially offer a sustainable method for the humidification and cooling of indoor air but only a small number of studies have investigated this. In an early study in an office environment (32 m^3 volume), researchers reported a small increase of 0.08% in RH and a reduction in the accumulation of PM when plants were introduced, occupying 5% by volume of the room (Lohr & Pearson-Mims, 1996). However, the rooms were occupied, and the study did not take account of the occupants, their activities, or the ventilation in the room.

A later study using sealed small-scale chambers (27 L) showed that the addition of plants (7% of chamber volume) was associated with an increase in RH of 15-60% and a reduction in $PM_{2.5}$ of 50-90%, depending on the plant species and type of particle; there was a greater reduction in hydrophilic particles at higher RH (Ryu et al., 2019). There may therefore be added benefits of particulate removal from using plants to humidify dry indoor air.

One study measured the RH levels in sealed chambers (volume 0.21 m^3) at light intensity of 330 lux (4.8 $\mu mol\ m^{-2}\ s^{-1}$) and estimated the water vapour and CO_2 production of eight indoor plant species, over 6 hours using mass balance equations (Panyametheekul et al., 2019). The substrate surface was sealed so water vapour emission was due only to plant transpiration. The estimated transpiration rates varied with species, the highest were for *Nephrolepis exaltata* (3.3 x10 ^{3} mg h^{-1}) and *Epipremnum aureum* (2.7 x10^3 mg h^{-1}), the RH levels in the chambers increased from 59% to 92%, and from 58% to 71% respectively. These species also had the largest leaf areas and highest number of stomata per plant out of all the plants tested, which would account for the high transpiration rates.

To compare C3 and CAM species, another study measured the ET rates of *Chlorophytum comosum* and *Crassula argentea* over 24 hours in chambers (16.14 m^3) during periods of light and dark (Kerschen et al. 2016). The ET rate of *Chlorophytum* was significantly higher during the light periods compared to the dark, whereas the ET rate of *Crassula* was more constant. All plants showed higher ET rates at 60% RH compared to 25% RH, showing that the species and RH of the environment can both significantly affect the plant ET rate. The study was limited to two species, one temperature and two settings of RH and further studies are needed with more species and environmental conditions to broaden the findings. Another study by Gubb et al. (2018) measured the ET rates of seven indoor plants in an office environment with low light intensity (10 µmol m^{-2} s^{-1}). They showed that higher ET rates co-occurred with high CO_2 assimilation and the ET decreased with decreasing soil moisture content. The ET rates varied with species and the highest rates were for *Hedera helix* and *Spathiphyllum wallisii* 'Verdi' (Gubb et al., 2018). The study did not take account of the ventilation rates or other varying environmental conditions within the experimental laboratory.

In the study by Su & Lin, (2015) cited earlier (1.2.5.2), a green wall (area 5.7 m^2) comprised of 189 *Asplenium nidus* plants installed in a sealed room of 38.9 m^3 volume (0.147 m^2 of plants m^{-3}), was associated with a 10% increase in RH and 2°C decrease in T_a over 6 hours. The increase in RH was assumed to be all due to plant transpiration as the room was unoccupied and the substrate surface was sealed with foil (Su & Lin, 2015). It could be expected that the increase in RH would be higher due to evaporation from the substrate, if the surface of the pots and substrate had not been sealed.

In a study by Torpy, Zavattaro, & Irga (2017), an increase of ~ 10% RH over 40 minutes, was measured in laboratory chamber studies (15 L volume, at 23 ± 2°C) using one plant per chamber of either *Chlorophytum comosum* or *Epipremnum aureum.* The tests were repeated with 16 plants in a chamber of 0.216 m^3 volume and the RH increased by ~40-50% over 40 minutes. However, when the trials were scaled up in a simulated room (15.7 m^3) with one m^2 of plant wall surface and an air leakage rate of 0.86%, there was no increase in the room RH over 40 minutes and changes in the room temperature were not more than 3°C. It is difficult to directly compare these results with those of Su & Lin (2015), as the two studies used different plant species, room volumes and test conditions but both studies show a significant increase in room RH associated with indoor plants.

Other studies have reported RH increases associated with plants in newly-built apartments (Lim et al., 2009) and a school classroom (Tudiwer & Korjenic, 2017; Smith, Tucker, & Pitt, 2011) but the water vapour emitted from the newly constructed buildings, ventilation rates, outdoor weather conditions, and the occupants or their activities, all of which can significantly impact the RH, were not considered.

By contrast, the introduction of a green wall into a corridor in a University building in Australia, did not increase the RH compared to a corridor without any plants (Ghazalli et al., 2018). The authors suggest this could be due to differences in the opening and closing of doors, or of the number of people using each corridor (Ghazalli et al., 2018). However, there was significant increase in the number of people using the corridor with the greenery, suggesting people prefer greened spaces and that careful positioning of indoor plants can be used to alter human traffic flow within buildings. A study by Mangone, Kurvers, & Luscuere (2014) found the presence of a mixture of 12 species of short and tall plants on desks or in floor planters, did not significantly impact the indoor T_a or RH within a large office over 4 seasons, where a mixed mode thermal conditioning system was in operation. However, the plants were associated with a significant positive impact on the thermal comfort of occupants (8-12% more comfortable) over all seasons, suggesting the presence of plants can affect participants' psychological perception of their thermal comfort. The authors concluded that the introduction of plants in the right quantities could lead to potential energy savings by allowing the indoor heating and cooling set points to be decreased/increased (Mangone, Kurvers, & Luscuere, 2014).

1.2.5.5 Plant processes influencing CO_2 uptake and air humidification

The removal of CO_2 and the addition of water vapour by plants relies on photosynthesis and evapotranspiration respectively; it is therefore necessary to understand these processes and the factors which influence their efficiency within indoor environments.

1.2.5.5.1 Photosynthesis

Plants use photosynthesis to produce carbohydrates for growth and the resultant gaseous exchange sequesters CO_2 from the atmosphere and releases O_2. Gases, including CO_2 and water vapour, enter and leave the plant by diffusion through stomata located in the leaves, and by adjusting the stomatal aperture, the leaves control the gas exchange (Hetherington & Woodward, 2003; Mansfield, Hetherington, & Atkinson, 1990). The size, density and speed of opening of the stomata vary considerably across species and in response to the environmental conditions (Kardiman & Ræbild, 2018a; Fanourakis et al., 2010; Zeiger, 1983). Drought/soil water deficiency, low ambient humidity, darkness and CO_2 concentrations above 750 ppm can cause stomatal closure depending on the plant species, whereas increase in light intensity, broadly speaking although depending on the wavelength, induces stomatal opening (Lüttge, 2018; Kim et al., 2004; Zeiger, 1983). The response to light also depends on the type of pathway the plants utilise for photosynthesis; plants which utilise C3 photosynthetic pathway typically display a diurnal pattern of stomatal opening with low stomatal conductance during the night and high during the day (Kardiman & Ræbild, 2018a). Plants which use crassulacean acid metabolism absorb light energy during the day and use it to fix CO_2 molecules during the night, thus their stomata remain closed during the day to conserve water (Lee, 2010).

1.2.5.5.2 Light and photosynthesis

Photosynthesis occurs within chloroplasts, where photosynthetic pigments, chlorophylls and carotenoids, absorb a range of light wavelengths but these are mostly the blue (400-500 nm), orange and red wavelengths (600 -700 nm) of the visible spectrum, known as the photosynthetically active radiation (PAR) range (McDonald, 2003). Light energy is composed of photons and their energy is inversely proportional to the wavelength (McDonald, 2003). Photosynthesis depends on the number of photons absorbed by the chloroplasts and the effective light quantity for photosynthesis is called the photosynthetic photon flux (PPF), measured in µmol $m^{-2}\,s^{-1}$ (Shimazaki et al., 2007; McDonald, 2003; Salisbury & Ross, 1992). Photosynthesis therefore depends on the light wavelength.

1.2.5.5.3 Light Compensation Point (LCP)

The net CO_2 assimilation of a plant leaf increases in response to increasing light intensity and can be plotted in the form of a light response curve (Lobo et al., 2013). The irradiance at which the net CO_2 exchange is zero, i.e., where the release of CO_2 from respiration equals the uptake from photosynthesis, is the 'light compensation point' (LCP). Maximum CO_2 assimilation is reached at the light saturation point (I_{max}), after which point increasing light intensity does not result in any further increase of photosynthesis (Lobo et al., 2013; Hodson & Bryant, 2012). For some plants increasing the light intensity beyond this point can lead to photoinhibition and potentially damage the plant (Salisbury & Ross, 1992). For indoor plants to achieve net CO_2 assimilation the light intensity must exceed the LCP. Several studies have determined LCPs for potted plants, ranging from 10 µmol $m^{-2}\,s^{-1}$ to 150 µmol $m^{-2}\,s^{-1}$, highlighting there is considerable variation depending on the species and the individual plants (Gubb et al., 2018; Treesubsuntorn & Thiravetyan, 2018; Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012). The acclimatisation treatment of indoor plants can also affect the plant LCP; Torpy, Irga, & Burchett (2014), showed that plants acclimatised under high room light intensity (90 ± 10 µmol $m^{-2}\,s^{-1}$) had higher LCPs and higher photosynthetic rates than the same species acclimatised under lower light intensity (10 ± 2 µmol $m^{-2}\,s^{-1}$).

1.2.5.5.4 Lighting within buildings

Within buildings, lighting is normally measured in units of illuminance called lux (lx), one lux is the equivalent of one lumen per square metre (CIBSE, 2015) (The Society of Light and Lighting, 2012). Lux is based on the Photopic Response Curve which provides a standardized measure of the response of the human eye to light at different wavelength (Quill et al., 2007). The bell-shaped curve extends from approximately 400 nm to 700 nm, and peaks at 500 nm (Quill et al., 2007). The spectrum and intensity of indoor light varies depending on the light source and the building design, best practice guidance for office lighting recommends providing a minimum light intensity of 300 lux to 500 lux (CIBSE, 2015). There is no universal conversion from lux to PPF as it depends on the spectrum of the light source, however one study determined that a plant illuminated with white LEDs, of 1000 lux approximated to 15 µmol s^{-1} m^{-2} PFDD (Sharakshane, 2017).

There is therefore a conflict between the ideal light provision required, both in intensity and wavelength, for humans and plant growth within indoor environments.

1.2.5.5.5 Evapotranspiration

Evapotranspiration (ET) is the combined process of evaporation of water from the substrate and plant surfaces and transpiration from plant. During evaporation, liquid water changes to water vapour and is released, the process is fuelled by heat energy from the air resulting in a localized cooling effect around the plants (Pérez-Urrestarazu et al., 2016; Novak, 2012). Transpiration is the process through which plants absorb water from the soil through their roots and lose it by evaporation through stomata in their leaves (Lüttge, 2018). It is driven by a gradient in water vapour density from within the leaf to the atmosphere beyond the leaf’s boundary layer (Schuepp, 1993). A waxy cuticle on the leaf surface restricts the diffusion of water so water vapour passes through the stomatal openings found on the underside or top surface of the leaves (Salisbury & Ross, 1992). When the stomata close, resistance to vapour loss is high thus reducing water loss; when stomata open, resistance is low and water loss increases (Salisbury & Ross, 1992). Transpiration rates have been shown to be affected by environmental factors such as leaf and air temperature, RH, air vapour pressure, air movement and light (Kemp, Hadley, & Blanusa, 2019; Charoenkit & Yiemwattana, 2017, 2016). During times of drought the plant seeks to conserve water and thus the ET rate reduces in response to decreasing soil moisture concentrations (Gubb et al., 2018). The species and physical characteristics of the plant such as the size, the leaf (area, density, surface) and the canopy (shape, size) have also been shown to influence the ET rate (Kemp, Hadley, & Blanusa, 2019; Gubb et al., 2018; Raji, Tenpierik, & Van Den Dobbelsteen, 2015).

1.2.5.6 Summary of the findings from studies on indoor plants and IAQ

The results from small-scale studies have demonstrated that with sufficient light, indoor plants can measurably reduce the CO_2 concentration of the air. The plant effectiveness depends on numerous factors including plant species, light intensity and photosynthetic pathway. The impact on the CO_2 concentration ranged from, reductions of 0-40% per hour, to net increases of the CO_2 concentration. It is difficult to make direct quantitative comparisons of the CO_2 removal rates for plants across different studies due to the wide variation in experimental testing conditions and plant species. Most studies have been conducted over only short periods of time due to the excessive build up humidity in the small, sealed chambers and only very few studies have verified the findings at room scale.

Small-scale chambers clearly show that indoor plants can add water vapour to the indoor air with studies reporting increases in the RH level of the chamber air from 10-60%. The increases are dependent on the plant ET rate which has been shown to vary with plant species. Although the ET rate is influenced by various environmental parameters, such as T_a and RH few attempts have been made to identify how the changing T_a and RH of the indoor environment affects the ET rate of different plant species and therefore their potential for humidifying the indoor air.

Due to the constantly changing and increasing RH in the chambers, measurements on a small scale of the impact of plants on the RH of the air are difficult. Rarely have the findings from small-scale RH studies been verified at a room scale.

The difficulties caused by the build-up of humidity and the restrictions imposed by the chamber size, limit the extent to which measurements of the impact of plants on CO_2 and RH concentrations can accurately predict their likely impact at room scale. However, chamber scale studies play an essential role in understanding the performance of plants under controlled conditions. Based on the results of numerous chamber scale studies in the literature and estimates of the room air exchange rates, several authors have proposed that indoor plants will have a limited impact at a room scale for VOC or CO_2 removal in real world situations (Cummings & Waring, 2019; Waring, 2016; Llewellyn & Dixon, 2011).

Studies of the impact of plants within real indoor environments on CO_2 and RH have shown varying results, from no impact to 0% -25% reduction of CO_2 concentrations and no change in RH to an increase of 10% in the room RH over 6 hours. The test period for the calculation of pollutant removal rates varied extensively between studies from less than one hour to months, so removal rates measured in one study are not directly comparable with another. For the maximum benefit of building occupants, a more detailed understanding of how different species impact the IAQ during the working day is needed.

Often in real-world studies, several factors which have a major impact on CO_2 concentrations and humidity within buildings have typically not been considered such as; the ventilation rate, volume and construction of the room or the occupants, their density and their activities and the external weather conditions. RH is inextricably linked to T_a, but rarely have the changes in T_a been accounted for in the RH changes determined. A wide variety of plant species and quantities have been used and factors which can influence the plant activity such as the light intensity, T_a and RH are often overlooked or not provided. Environmental conditions such as T_a and RH show seasonal variation, but few studies have investigated how the plants perform over different seasons.

1.2.6 The psychological wellbeing of building occupants

1.2.6.1 The importance of psychological wellbeing

When indoor plants are introduced into a room, they affect the air quality, and they impact the visual aesthetics of the space. Research has shown that people’s perceptions of and satisfaction with the indoor environment is affected by both physical and psychological factors, which can in turn affect their wellbeing, comfort and productivity (Al Horr et al., 2016; Clements-Croome, 2015; Mangone, Kurvers, & Luscuere, 2014; Bluyssen, 2010, 2014; Nieuwenhuis et al., 2014; Marmot & Wilkinson, 2006).

The attractiveness of the workplace is important as it can influence complaints and absenteeism; a nationwide UK survey of 200 managers reported that better work environments could lead to productivity gains of 19%, the equivalent of £135 billion per year (Clements-Croome, 2006). A survey of 7600 office workers, in 16 countries reported that indoor plants were the second most desired element within the office environment and a lack of greenery has been associated with dissatisfaction with the work environment (Cooper & Browning, 2015; Clements-Croome, 2006).

1.2.6 2 Definition of wellbeing

When reviewing the literature on “wellbeing” it is apparent that the term spans multiple disciplines and numerous definitions exist. According to the World Health Organization (WHO) ‘Health is a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity’ (WHO, 1946). Mental health is defined as a state of wellbeing in which every individual realizes his or her own potential, can cope with the normal stresses of life, can work productively and fruitfully, is able to make decisions and contribute to her or his community (WHO, 2004)

The Chartered Institute of Personnel and Development defines wellbeing at work as: "creating an environment to promote a state of contentment which allows an employee to flourish and achieve their full potential for the benefit of themselves and their organisation" (Fenton et al., 2014).

1.2.6.3 Theoretical models describing wellbeing

Since Maslow's early Theory of Human Motivation (Maslow, 1943), numerous models have sought to relate the influence of multiple factors, including the physical environment and IEQ, on peoples' wellbeing and productivity at work (Kim & de Dear, 2012; Kim & De Dear, 2012; Bluyssen, 2010; Chappells, 2010; Haynes, 2009; Vischer, 2008; Clements-Croome, 2006; Morris et al., 2006; De Looze, Kuijt-Evers, & Van Dieën, 2003; Warr, 2002).

Psychological wellbeing can be considered from a subjective point of view known as subjective wellbeing (SWB), which relates to how a person feels about themselves (Diener, Oishi, & Tay, 2018) and from a cognitive performance viewpoint which is determined by effective functioning of the brain (Rich, 2008). SWB includes a hedonic dimension which focuses on happiness and a eudaimonic dimension which focuses on meaning and self-realisation, which is referred to by supporters of positive psychology as *human flourishing* (Seligman, 2011; Turner, Barling, & Zacharatos, 2002; Ryan & Deci, 2001).

In her model of environmental comfort, Vischer (2008) posits that people need more than simply health and safety in buildings to be comfortable. She proposes that the design of the workplace and people's likes and dislikes affect how they feel and their work performance. She advocates that in assessments of environmental comfort, occupants should be asked how much they like the environmental conditions or the office design and how much do they feel it affects their productivity (Vischer, 2008).

Numerous elements of the physical environment can influence the wellbeing of building occupants, the SALIENT checklist (Dolan, Foy, & Smith, 2016), describes seven elements that can influence wellbeing in buildings: Sound, Air, Light, Images, Ergonomics, Nature and Tint (colour). Other studies have also shown that colours have an influence on wellbeing in the workplace: blue, green and yellow, are associated with motivation, productivity, happiness, harmony and peacefulness (Cooper & Browning, 2015; Clements-Croome, 2006; Lacy, 1996). The colour green, typical of nearly all indoor plants, has also been shown to increase creativity compared to white, blue, grey and red (Lichtenfeld et al., 2012).

The Flourish model proposed by Clements-Croome and others (Clements-Croome, Turner, & Pallaris, 2019; Clements-Croome, 2006) shown in Figure 1.1, links people's productivity to their SBW, feelings and work environment. It brings together motivation and happiness theories and provides a framework for assessing the design of the workplace environment and evaluating the outcomes.

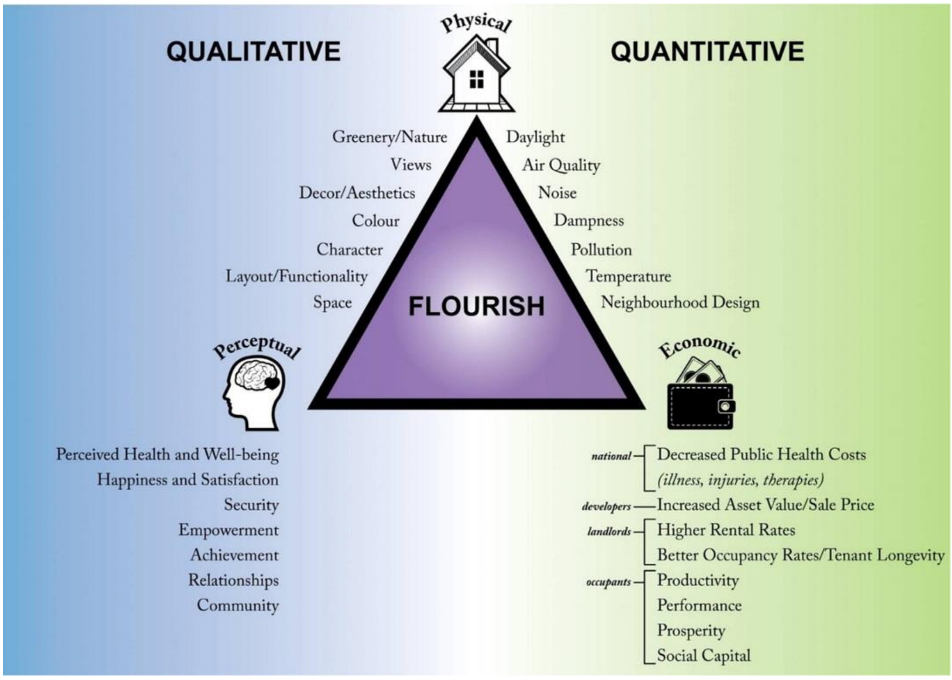


Figure 1.1: Flourish model Source: (Clements-Croome, Turner, & Pallaris, 2019)

The model is based on three issues: the environmental factors, the perceptions and feelings people have in various environmental settings and the economic consequences of the environments created (Figure 1.1). In this model both greenery and indoor air quality are included as elements which impact people's ability to thrive and flourish, thus recognising the important contribution that indoor plants can make.

1.2.6.4 The benefits of interaction with nature in built environments

In built environments where people lack contact with nature, incorporating natural elements have been shown to reduce stress and improve people's SWB and satisfaction with the indoor environment (Grinde & Patil, 2009; Kellert, Heerwagen, & Mador, 2008; Bringslimark, Hartig, & Patil, 2007). The benefits include quicker recovery time in hospital, higher pain tolerance, improvements in mood and cognitive performance, reduced stress and better mental health (Al Horr et al., 2016; Grinde & Patil, 2009; Bringslimark, Hartig, & Patil, 2009). In studies demonstrating the benefits of viewing nature on cognitive performance and mental health, the definition of nature used is very wide ranging from a single potted plant to a view of a nature reserve (Bratman, Hamilton, & Daily, 2012; Grinde & Patil, 2009; Berman, Jonides, & Kaplan, 2008; Hartig et al., 2003) and it is not clear which elements of nature impact the human psyche (Bratman, Hamilton, & Daily, 2012). In addition, the studies cover a wide variety of environments from outdoors, to schools, universities, healthcare and offices.

The Biophilic Hypothesis developed by Kellert & Wilson (1993), asserts that humans have a biologically-based, inherent need to connect with nature in order to achieve personal fulfilment. They postulate that the affiliation with nature was advantageous for survival of the human species during our evolutionary struggle (Kellert & Wilson, 1993). Biophilic design aims to incorporate features of nature, such as indoor plants, in building design (Kellert, Heerwagen, & Mador, 2008).

1.2.6.4.1 Attention Restoration Theory

Attention Restoration Theory (ART) (Kaplan, 1993, 1995; Kaplan & Kaplan, 1989), is one of two main theories which are used in the literature to explain the positive effects of indoor plants on human wellbeing. ART posits that cognitive attention can be split into two distinct components: directed attention which requires effort and can be consciously controlled and; involuntary attention which requires no effort. It is proposed that tasks which require focus and prolonged mental effort lead to directed attention fatigue, which requires restoration (Kaplan, 1995). Supporters of ART claim that modern urban life requires more directed attention and that certain environments such as nature, or viewing scenes of nature provide opportunity for this to be restored (Bratman, Hamilton, & Daily, 2012; Rich, 2008; Kaplan, 1995).

Workplace studies in support of ART, have shown that workers with views of nature, had fewer reported ailments, higher job satisfaction and improved scores in attention tests compared to those without (Berman, Jonides, & Kaplan, 2008; Kaplan, 1993, 2007; Berto, 2005). A study using electroencephalography (EEG) found that viewing natural scenes requires less attentional and cognitive processing compared to viewing urban ones (Grassini et al., 2019). However, several authors have critically reviewed and questioned the evidence and theoretical assumptions supporting ART, arguing that a fleeting episode of involuntary attention would be insufficient to support a full restorative experience (Joye & Dewitte, 2018; Hartig & Jahncke, 2017; Ohly et al., 2016; Joye & van den Berg, 2011).

Across all the studies, a wide range of cognitive tests were used, which tested different cognitive demands for different experiences of nature and overall, the evidence for ART appears inconclusive.

1.2.6.4.2 Psycho-Evolutionary Theory or Stress Reduction Theory

The alternative theory to ART is the Psycho-Evolutionary Theory or Stress Reduction Theory (SRT), posited by Ulrich (Ulrich, 1983) which proposes that nature has a stress reducing or restorative power (Ulrich, 1983; Ulrich et al., 1991). He bases his theory on humans having an evolutionary response to nature, where being able to rapidly respond to threats, and to recognise natural places which could provide safety and shelter, enabled our survival. He argues that viewing or being present in nature can elicit automatic psychological and physiological responses to reduce stress, which can be measured, for example through improved mood or lowered blood pressure (Ulrich et al., 1991). In developing his theory he carried out numerous studies measuring people's responses to views of landscapes, this included studies in healthcare settings showing quicker recovery times in patients who had a view of nature (Ulrich et al., 1984, 1991; Ulrich, 1986).

A critical evaluation of numerous studies, concluded there was evidence of a stress reducing effect from viewing nature, but there was insufficient evidence to support the idea that this was due to an evolutionary response as described in SRT (Joye & van den Berg, 2011).

1.2.7 The impact of indoor plants on the wellbeing of building occupants

Indoor plants provide a means of bringing nature into indoor environments and numerous studies have evaluated their benefits on human wellbeing.

Studies carried out in three large commercial offices in the UK and the Netherlands (Nieuwenhuis et al., 2014), showed the introduction of indoor plants significantly increased workplace satisfaction and self-reported levels of concentration after 2 weeks and 3.5 months. Productivity and perceptions were assessed through psychological tests and surveys, they found improvements in both cognitive performance and subjective wellbeing in the presence of plants. The plants could be generating a restorative effect as proposed by ART, or workers could have felt more engaged due to the perceived care by the managers, or the visual aesthetics of the plants may have evoked a hedonic response. Workers perceived that the plants improved the IAQ although this was not physically measured in the study, raising the question - did the plants impact the IAQ and if so, did the changes in IAQ or the appearance of the plant affect people's responses.

Rarely in the literature studies have the differences in indoor plant species on participant's responses been considered, but a study in a test laboratory room showed that the introduction of plants which were perceived to be more beautiful increased participants' pro-social (helpful) behaviour compared to less beautiful plants (Zhang et al. 2014). The effect was greater in people who appreciated natural beauty and was linked to positive emotions. However, the participants in the study were all female students and may not be representative of typical office workers; females were suggested to also be more likely to enjoy plants and engage in helpful behaviours than males (Zhang et al. 2014). The task used to measure pro-social behaviour was the willingness to help with an origami task, but this may not be representative of tasks in work related environments.

Numerous cognitive tests have been used to assess the impact of plants on the productivity of office workers. The addition of indoor plants to a windowless room, were associated with increased reaction times and self-reported attentiveness and lower blood pressure, in participants undertaking a computer productivity test (Lohr, Pearsons-Mims, & Goodwin, 1996). As stress reduction was indicated by lowered blood pressure, the results could support Ulrich's SRT. However, a preliminary study by the same researchers, using a different productivity task, showed no improvement in reaction times with plants (Lohr, Pearsons-Mims, & Goodwin, 1996). This suggests that the effect of plants on cognitive performance is influenced by the cognitive test employed; this is supported by an earlier study which showed that a window view in the workplace was associated with a decrease in performance in repetitive tasks but improved performance in creative tasks (Stone & Irvine, 1994). When considering the effect of views from a window there is a confounding effect of increased daylight which could also influence wellbeing. To separate the effects of window views and interior plants, one study measured participants' physiological and psychological reactions whilst participants viewed images of different office environments (Chang & Chen, 2005). A window with a view of nature plus indoor plants had the greatest effect on lowering anxiety. The addition of plants increased the positive physiological, and psychological effects. However, a higher proportion of female to male participants (28:10) may have influenced the results and responses to images may not be representative of real office environments.

Researchers have also sought to understand the effect of plant quantity or visibility on productivity. In a small university office based test, increasing the plant density from none to moderate or high, worsened participants performance in productivity tests, but was associated with improved mood and increased the perceived attractiveness and comfort of the office (Larsen et al., 1998).The researchers proposed that the plants may have reduced concentration in the simple sorting task used and that participants were distracted as their improved mood caused by the plants prompted them to recall more irrelevant information. This study used tests of very short duration (3 x 1 minute) which may not be indicative of productivity over the longer term and a very large number of plants which would probably be impractical in a real office.

To build on the work by Larsen et al. (1998), Shibata and Suzuki (2002) used slightly longer tests (10 min) and included a creative and repetitive task. Plants were placed either in front of participants or to the side. The results showed a gender difference in both tests with women scoring higher than men. There was a weakly significant increase in scores with plant visibility for males in the association task, but no significant difference in the sorting task. A slight, but not significant, decrease in the female scores was observed with increasing plant visibility. In contrast to the findings of Larsen et al.(1998) in this test the plants had no impact on mood.

These two studies show contrasting results for the impact of plants on the sorting task, making it difficult to draw a conclusion about the impact of plants on productivity but there is some indication that plants could be positively influencing the creativity task, which has some support from other creativity studies (Rich, 2008). A larger study involving a range of wellbeing tests and different type of plant exposure (live plants, pictures of plants and interaction with plants), showed only a positive impact in a maths test and response time test after participants interacted with plants, but no impact on mood (Rich, 2008). These studies suggest that the location and density of indoor plants in the office can affect people's concentration and wellbeing, but it isn't clear as to what the ideal planting arrangements are to achieve maximum benefit for workers. Other studies found the amount of greenery a person sees did not significantly affect their physiological responses (Choi 2016) and the amount of greenery a person sees in their sight line appears to be more important than the number of plants (Han 2020).

Two studies investigated the impact of exposure to plants during breaks on fatigue recovery and showed partial evidence for a positive effect of plants: in one test there was a positive but non-significant increase in task scores with plant presents and in the second there was initially a significant improvement with plants but this wasn't sustained during ongoing fatigue (Raanaas et al., 2011; Shibata & Suzuki, 2001).

1.2.7.1 The visual aesthetics of the indoor environment

The visual aesthetic experience of the environment can affect people's perceptions, moods and stress levels (De Korte, Kuijt, & Van Der Kleij, 2011; Kaplan & Kaplan, 1989). Office environments with plants are typically perceived as more attractive (Nieuwenhuis et al., 2014; Larsen et al., 1998). Studies in healthcare (Dijkstra, Pieterse, & Pruyn, 2008), retail (Brengman, Willems, & Joye, 2012) and learning environments (van den Bogerd et al., 2021) have shown stress-reducing effects of plants, which have been partially explained by the increased attractiveness of the rooms. Viewing plants in laboratory studies have been associated with reduced stress indicators such as heart rate variability and blood pressure (Choi, Park, Jung, J Lee, et al., 2016; Lohr, Pearsons-Mims, & Goodwin, 1996). These studies have focused on the visual aspect of the plants but other factors of plants such as the smell or the impact on acoustics or impact on air quality could be involved. In addition the green colour of the plants may be having a confounding effect as colours in the workplace design are known to affect wellbeing (Cooper & Browning, 2015; Clements-Croome, 2006; Lacy, 1996).

Researchers in South Africa found that improvements in work performance and evaluations of the work environment associated with indoor plants, in a laboratory study were not reproduced in two field studies in call centres. But there was a suggestion that the perceived attractiveness of the plants could have an influence and that plants might only be beneficial in contexts where participants perceive them to be attractive (Thatcher et al.,2020).

The physical appearance of the plant is primarily determined by its shape, colour, texture and size. Research involving trees and flowers has shown that shape and colour significantly affect people's emotional and physiological responses (Hůla & Flegr, 2016; Muderrisoglu et al., 2009; Kaufman & Lohr, 2004; Summit & Sommer, 1999). Several authors determined that the spreading canopy shape of trees was preferred to rounded or conical forms and they suggested this aligned with the Savanna hypothesis – which is related to evolutionary theory that spreading trees increased our chances of survival on the open savanna landscapes (Falk & Balling, 2010; V. I. Lohr & Pearson-Mims, 2006; Sommer & Summit, 1995; Heerwagen & Orians, 1993). Other studies have shown that people prefer pyramid shaped trees (Muderrisoglu et al., 2009) and curved visual objects (Bar & Neta, 2006). In an assessment of flower beauty by Hůla & Flegr (Hůla & Flegr, 2016), shape was found to be more important than colour. Healthiness, bushiness and shape have been identified as key factors affecting purchasing decisions for outdoor ornamental plants (Brascamp, 1996).

1.2.7.2 Summary of studies investigating indoor plants and wellbeing

The addition of indoor plants affects the visual aesthetics of a room and overall, there is sufficient evidence from the literature, including measurements of brain activity and physiological stress indicators, to show that the presence of indoor plants can positively impact the psychological wellbeing of the occupants. A wide range of tests, methods and questions have been used in the studies to assess the impact of plants on participant's wellbeing. It is evident from the studies that when assessing cognitive wellbeing, the choice of test can influence the outcomes and the effect of plants on productivity depends on the type of task being undertaken.

Studies also showed that the presence of indoor plants can affect the occupant's perceptions of IAQ, thermal comfort and subjective wellbeing. A wide variety of plant species have been used in the studies but virtually no studies have considered the impact of the different visual characteristics of the individual species on the results, or how people's preferences affect their responses. The appearance of the plant also changes when it is sick or poorly maintained but none of the studies have investigated the effect of neglected plants on people's wellbeing.

1.2.8 Knowledge gaps identified from the literature review

This review of previous studies has shown that plants can reduce CO_2 concentration and add water vapour to the indoor air but their effectiveness within indoor environments is still under debate (Cummings & Waring, 2019; Gubb et al., 2018; Cheung, 2017; Torpy, Zavattaro, & Irga, 2017). Much of the work has been conducted in small chambers and few studies have verified the results in real office environments. Real-world studies present many challenges but if plants are to contribute to future indoor air improvement strategies, it is essential that reliable data from studies from real-world indoor environments is obtained to verify the findings from laboratory studies. This research aims to provide new quantitative data to contribute to this body of knowledge.

The addition of indoor plants can also benefit the psychological wellbeing of building occupants and influence people's perceptions of IAQ and thermal comfort. The visual appearance, including the shape and colour of indoor plants may influence people's responses to their environment and their subjective wellbeing although no studies have investigated this. If designers, employers and building mangers are to invest in plants and achieve maximum benefits for the building occupants, it is important to know how the appearance of the plant affects people's perceptions and responses. This research aims to provide new knowledge to further this understanding.

1.2.9 Research Aims and Objectives

1.2.9.1 Overall aim of the research

The overarching aim of this research is to investigate and quantify the potential for potted plants with different traits, to improve the IAQ within indoor office environments, and to determine how the physical traits of the plants affects people's perceptions of their impact on IAQ and their own subjective wellbeing.

The research will use a multi-disciplinary approach to address the aims and will focus on naturally ventilated office buildings.

1.2.9.2 The research objectives

1. To determine how different plant species and numbers of indoor plants affect the CO_2 concentration in sealed, laboratory-scale chambers. **(Chapter C3)**

2. To investigate the impact of indoor plants on the CO_2 concentration in a naturally ventilated office environment, over different seasons. **(Chapter 4)**

3. To determine the impact of different indoor environmental conditions on the ET rate of different plant species in controlled environmental chambers. **(Chapter 5)**

4. To investigate the impact of plants on the humidity in a naturally ventilated office environment over different seasons. **(Chapter 6)**

5. To measure people's preference and response to the appearance of indoor plants displaying different physical characteristics. **(Chapter 7)**

6. To determine if the plant appearance and shape affects people's perception of its impact on IAQ, RH or SWB. **(Chapter 7)**

1.2.10 The thesis structure

This thesis consists of eight chapters. Table 1.1 summarises the structure and content of the chapters and how these relate to the research objectives outlined in 1.9.2.

Chapter	**Purpose**	**Objectives addressed**
1 **Introduction and Literature Review**	To introduce the research, provide the project background and aims and objectives. To review the state of existing knowledge from the literature. To identify knowledge gaps and methodologies that can be used to answer the research questions.	
2 **Materials and Methods**	To provide details of general materials and methods used throughout the research.	
3 **Reduction of CO_2 within experimental chambers**	To present and discuss results of laboratory scale experiments to identify impact of plants on CO_2 reduction in controlled environments. The best performing plant species for use in field trials are identified.	1
4 **Room scale studies of the impact of plants on the reduction of CO_2**	The results of experiments conducted in real offices over different seasons are presented and discussed. This includes measurements of the ACH of each office and the impact of plants on CO_2 reduction.	2
5 **Impact of T_a and RH on ET rates within experimental chambers**	To present and discuss results of experiments conducted in controlled environmental chambers, to measure the ET rate of selected plant species under different environmental conditions.	3
6 **Room scale studies of the impact of plants on indoor humidity**	The results of experiments measuring the impact of plants on the T_a and absolute humidity within real offices over different seasons are presented and discussed. A comparison with the results from a theoretical model are included.	4
7 **The appearance of indoor plants and their effect on people's responses**	To present and discuss results of a survey conducted to determine how the plant appearance affects people's emotional responses and their perceptions of its impact on their SWB and the IAQ.	5 and 6
8 **Discussion Conclusions and Recommendations**	This chapter draws together the findings from the research into a final discussion and conclusions.	All

Table 1.2: Thesis structure

Chapter 2

General Materials and Methods

2.1 Introduction and summary of the experiments

This chapter provides a summary of the shared methods, equipment and plant material used for the experiments investigating the impact of plants on the IAQ (Chapters 3-6), additional details of the methods used are contained within each chapter The methods used to investigate people's psychological responses to plants are detailed separately, in Chapter 7.

All experiments were conducted at the University of Reading, Whiteknights campus, Berkshire, UK in three locations: i) the glasshouse and controlled environment complex of the School of Agriculture, Policy and Development; ii) Chancellor's building and iii) the Technologies for Sustainable Built Environments (TSBE) Centre, JJ Thomson building. Table 2.1 provides an overview of the experiments and the locations where they were conducted. Environmental conditions were measured with equipment outlined in Table 2.2 and tailored to each experiment as detailed separately in the relevant chapters.

Experiment	**Location**	**Main equipment**
Reduction of CO_2 Chamber-scale experiments **(Chapter 3)**	TSBE Centre laboratory	Hobo MXII02 sensors /data loggers Two purpose made chambers
Plant light response curves Plant leaf area **(Chapter 3)**	Glasshouses and plant laboratories	Infra-red Gas Analyser WinDIAS Leaf image analysis system
Reduction of CO_2 Office-scale studies **(Chapter 4)**	TSBE Centre offices Chancellor's building Offices	Hobo MXII02 sensors/ data loggers
ET rates of plants - environmental chambers Plant leaf area **(Chapter 5)**	Controlled environment complex and plant laboratories	Environmental chambers Hobo MXII and Lascar Easy log sensors Balances and weight loggers WinDIAS Leaf image analysis system
Office-scale humidity studies **(Chapter 6)**	Chancellor's building offices	Hobo MXII02 sensors/ data loggers

Table 2.1: Summary of the experiments conducted, the location and the main equipment used.

Parameter measured	Instrument	Accuracy
Air temperature % RH CO_2	Hobo MX1102 sensor and data loggers Onset Computer Corporation, Bourne, MA, U.S.A	Temperature ±0.2°C from 0° - 50°C Humidity ±2% RH (from 20 - 80% RH) to a maximum of ±4.5% at 25°C and ±6% < 20% RH and > 80% RH CO_2, ±50 ppm ±5% at 25°C <70% RH
Air velocity	Kestrel 4200 Pocket Air Flow Tracker Nielsen -Kellerman Boothwyn, PA USA	±1.04% within the airspeed range (3.59 to 19.93 m/s), and ±1.66% within the airspeed range (0.85 to 3.59 m/s)
CO_2	Q-Trak 7575 TSI electronics, High Wycombe, Bucks, UK	Range 0 to 5000 ppm CO_2, Accuracy ±3% or ±50 ppm CO_2, whichever is greater
Light	Testo 545 lux meter Supplier: RS components, Corby, Northants UK	0 -100000 lx Accuracy ± 8.5%
Photosynthetically active Photon irradiance	Skye SKP 215 PAR Quantum sensor Skye Instruments Ltd, Llandrindod Wells, Powys UK	Accuracy ± 5%
CO_2 assimilation	LCPro infra-red gas analyser (IRGA) ADC Bioscientific, Hoddesdon, Hertfordshire, UK	Chamber Temperature: -5°C to 50°C +/- 0.2°C accuracy
Leaf Area	WinDIAS Leaf image analysis system Delta-T Devices Ltd, Cambridge, UK	Accuracy ± 1%

Table 2.2: Details of the main equipment used for the experiments.

2.2 Plant material

A range of indoor plants were chosen to represent different physical characteristics, metabolisms (C3 and CAM), leaf types (shape, size, waxiness) and canopy shapes. The plants ranged in size, depending on the species, but within the species, plant height and stature were uniform. All selected plants are commonly used in commercial UK offices and homes, based on data from Ambius, a leading commercial plant installer and the Royal Horticultural Society (RHS) retail sales (personal communications). The plants were approximately two years old at the start of the research and were replaced with new two year old plants for Chapter 5. For a minimum of three months prior to the start of the experiments, and in between experiments, plants were kept in an indoor office environment within the TSBE Centre at ambient temperatures (17–25 °C), RH (30 - 60 %) and typical indoor office light levels (10–30 µmol m^{-2} s^{-1}, 650–1500 lux).

Characteristics of plants species used are detailed below. All chosen species are evergreen perennial plants, originating in (sub)tropical climates and have C3 photosynthetic metabolism, except *Sansevieria* which uses CAM metabolism. Photographs of species studied are presented in Figure 2.1.

***Asplenium nidus**,* a fern and part of the Asplenoiaceae family*,* is native to tropical south-eastern Asia, Australia and Africa (ARS, 2021). An epiphyte although can also be a terraphyte, it is typically found growing in tropical forests where it is shaded by trees and utilises filtered sunlight. It was chosen for its natural adaptation to low light, its frond leaves and previous studies which have reported it has good CO_2 removal capability (Su & Lin, 2015).

***Calathea majestica* 'White Star'** is a tropical plant part of the Marantaceae family, native to South American rainforests (NC State University, 2021) where it has a preference for bright shade. In response to darkness the leaves fold upwards (nyctinasty) to display the red undersides. It was chosen for its broad, striped leaves with red undersides, which are reported to help maximize the utilisation of low light and give the plant a striking appearance (Attenborough, 1995).

***Dracaena fragrans* 'Lemon Lime'** is a shrub/tree, part of the Asparagaceae family, a terraphyte and native to tropical Africa (NC State University, 2021). It was chosen for its waxy, lemon and lime coloured leaves with a broad pointed shape.

Dypsis lutescens is an evergreen palm tree and a member of the Arecaceae family. A tropical terraphyte, native to Madagascar which likes partial shade (Flora Fauna Web., 2019). It was chosen as an example of a popular indoor palm plant and because of its arching, pinnate, narrow pointed leaves which it is hypothesized would have low CO_2 removal per plant due to the smaller surface area.

Epipremnum aureum is a broadleaf, climber, part of the Araceae family, a facultative epiphyte found in moist forests worldwide where it has adapted to tolerate low light (NC State University, 2021). It was chosen as an example of a trailing plant, its ability to tolerate low light and its ease of maintenance.

***Ficus benjamina* ‘Danielle’** is a tree, native to Asia and Australia, part of the *Moracease* family. It was chosen for its woody structure, small leaves and its ability to tolerate a variety of growing conditions and is able to adapt from bright to low light (Starr, Starr, & Loope, 2003).

Sansevieria trifasciata* var. *laurentii is native to Africa and southern Asia and belongs to the Asparagaceae family. It was chosen as it is a succulent tropical plant and has adaptive features that enable it to withstand the effect of drought, such as the ability to store water in its tissue and its photosynthetic pathway utilises CAM metabolism which it is hypothesized would lead to low CO_2 uptake and transpiration during the daytime (Martin et al., 2019).

Asplenium nidus

Calathea majestica ‘White Star’

Dracaena fragrans ‘Lemon Lime’

Dypsis lutescens

Epipremnum aureum

Ficus benjamina ‘Danielle’

Sansevieria trifasciata var. *laurentii*

Figure 2.1: Representative images of the plant species used in the research. Images are based on original photographs of the plants used, but size of plants are not to scale

2.2.1 Growing medium, substrate moisture and plant watering

The plants were maintained in 3-L plastic containers with a professional pot bedding substrate (Clover peat, Dungannon, Co. Tyrone, UK) and a slow-release fertiliser feed (Osmocote, Marysville, OH, USA) was applied annually. Prior to the start of the experiments, preparation tests showed that the substrate was considered “saturated” at a substrate moisture content (SMC) of 60% (0.6 m^3m^{-3}) and “dry” below 20% (0.2 m^3m^{-3}) and for the purposes of this study SMC between 40-50% (0.4 -0.5 m^3 m^{-3}) was considered “well-watered”(Monteiro et al., 2016). Plants were watered 1 hour before experiments to maintain the SMC in the range 40 - 45%. The SMC was measured at the start of each set of experiments, in three locations per container using a capacitance- type probe (WET sensor) connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of ± 2.5%). The WET sensor was calibrated by Delta-T Devices prior to the start of the research and was used on the ‘organic’ substrate setting.

2.2.2 Plant dimensions

The plant height was measured from the top of substrate to top of canopy. Plant width was measured across the mid-canopy in two places. Measurements were made on 6-12 plants per species and the mean and standard deviation calculated. The measurements for the plants used in the different experiments are included in the relevant chapters.

2.2.3 Leaf surface area

The leaf area was measured using a WD3 WinDIAS leaf image analysis system and associated software WinDias 3.2 (Delta-T Devices Ltd, Cambridge, UK) The instrument was calibrated before each use. For *Ficus* plants, all the leaves were removed from two plants and placed on a light box with an overhead video camera, the leaves were held flat with a sheet of clear Perspex. For all other plants, destruction of the plants was not possible, so tracings were made of each leaf, from six plants of each species and the area of the paper cut outs were measured using the same method as above. The leaf areas were measured at the end of the CO_2 chamber experiments (Chapter 3) and at the end of the ET experiments (Chapter 5).

2.2.4 Leaf surface area to density ratio (LAD)

An estimate of the volume of the plant was made by assuming each plant’s canopy was cylindrical and calculating the volume of a cylinder (volume= $\pi r^2 h$). An estimate of the plant Leaf Area Density (LAD) was made by dividing the leaf area by the plant volume (LAD = Leaf area ÷ Plant volume).

2.3 IAQ measurements

Details of the equipment used to measure IAQ conditions is provided in Table 2.2. All equipment was calibrated professionally (Building Services Research and Information Association) prior to the start of the research and before each experiment in accordance with manufacturer’s instructions.

In these studies T_a refers to the air temperature.
Relative humidity (RH) is defined as the amount of water vapour contained within a given volume of air compared with the maximum amount the air could hold at a given temperature.
‘Moisture’ is used to describe the water vapour held in the air, when referring to indoor air studies and water vapour is used to describe the water vapour emitted from plants.

2.4 Data analysis and statistics

For all data analysis and statistics Excel, and SPSS (version 25) have been used.
Details of the various statistical analyses used are included within each chapter.

Chapter 3

The impact of plants on the reduction of CO_2 within experimental chambers

3.1 Introduction

From Chapter 1, CO_2 was identified as one of the most common gaseous pollutants in indoor environments and exposure to relatively small increases in CO_2 concentrations are associated with reduced cognitive performance and productivity (Fisk, 2000; Wargock et al., 2000; Mendell and Heath, 2005; Seppänen and Fisk, 2006). Whilst typically CO_2 concentrations in office environments are controlled by natural or mechanical ventilation systems (ASHRAE, 2013; CIBSE, 2006a, 2011), the need for sustainable alternatives has been established (Chenari, Dias Carrilho, & Gameiro Da Silva, 2016; Luengas et al., 2015).

Plants through the process of photosynthesis have the potential to remove CO_2 from indoor environments. Various studies have investigated the potential of indoor plants for lowering CO_2 concentrations in laboratory chambers; (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014; Oh, Jung, M. H. Seo, et al., 2011) and have shown that species choice, light intensity (Torpy, Irga, & Burchett, 2014), CO_2 concentration (Oh, Jung, M. H. Seo, et al., 2011) and substrate moisture (Gubb et al., 2018) can affect the plant CO_2 removal rate, understanding the response of the individual plants to specific conditions on a small scale is therefore important before room scale trials.

Light intensity, a key parameter affecting plant growth and photosynthesis (Kim et al., 2012) can be a limiting factor for plant photosynthesis within indoor environments (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014). The leaf light compensation point (LCP) is the light intensity at which the net removal of CO_2 by photosynthesis equals the output from respiration and therefore provides an indication of the lowest light intensity which must be exceeded in order to achieve net removal of CO_2 (Torpy, Irga, & Burchett, 2014). Although there are only a few previous studies which have measured the LCPs of indoor plants, these have shown there is a significant variation between and within species (Gubb et al., 2018; Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012). It is therefore important to understand the light requirements for the actual plants to be used in this research and to determine the LCPs for more species to add to the existing body of knowledge on indoor plants.

Planting density on an office scale is an important consideration as it can affect the attractiveness of the space and people's productivity (Shibata & Suzuki, 2002; Larsen et al., 1998). For example, increasing the plant density from 10 plants to 22 plants in an office of 31.3 m^3 volume, improved the appearance of the office and the mood of the participants but led to a decrease in their performance in a letter identification task (Larsen et al., 1998). However the impact of higher plant densities on IAQ benefits are unclear as a study by Oh et al., (2011), showed that increasing the leaf area of *Ficus benjamina* and *Dypsis lutescens*, within sealed chambers did not lead to a significant increase in CO_2 removal. There is therefore a need to understand how the efficiency of CO_2 removal for different species is affected by plant density.

Identifying the impact of plants on IAQ at a room scale has most practical relevance for determining the benefits of plants for buildings occupants. However, studies of CO_2 removal by plants in real offices present many challenges due to the lack of control and variability of the environmental drivers which affect the CO_2 concentration and plant function. Chamber scale studies are therefore a useful initial step to allow for the better control of the environmental parameters (e.g. light intensity, air exchange rate, temperature).

The focus of this chapter was therefore to investigate the impact of different indoor plant species on reducing CO_2 concentrations within small-scale chambers whilst other factors affecting CO_2 removal rate were kept constant, to provide a better understanding of the plant performance prior to room-scale studies.

The objectives of this chapter were therefore:

- To determine the light compensation points for different plant species
- To determine the CO_2 removal rate of different indoor plant species and to understand how this is impacted by plant density (quantity).
- To identify the plant species with the highest CO_2 removal rate and greatest potential for impacting the CO_2 concentration within indoor environments .

3.2 Materials and methods

A series of successive experiments were carried out in two purpose-made sealed chambers, situated in the TSBE Centre laboratory, University of Reading (UoR), Berks RG6 6AF UK, between January – June 2019. Seven plant species were tested at densities of one, three or six plants per chamber and each species and density was tested three times (total of 63 tests), to determine how the plant species and density affected the CO_2 removal rate.

3.2.1 Plant material

Seven indoor plant species; *Asplenium nidus, Calathea majestica* 'White Star', *Dracaena fragrans '*Lemon Lime*', Dypsis lutescens, Epipremnum aureum, Sansevieria trifasciata* 'Laurentii' *and Ficus benjamina* 'Danielle', common to the UK, were selected for the experiments to represent a range of different plant physical and physiological characteristics; plant vigour, leaf type (succulent and herbaceous), leaf shapes and size (rounded, pointed, narrow and broad) and photosynthetic metabolism (C3 or CAM) as described in Chapter 2. Six replicate plants per species were used for testing and were prepared and maintained as described in Chapter 2. The plants were watered 1 h prior to the start of each experiment to maintain the SMC at a starting level of 40-45%. Plant dimensions were taken at the start of the trials and leaf area was measured at the end of the trials (Table 3.1). All measurement techniques are described in Chapter 2.

3.2.2 Determination of leaf light compensation points

An LCPro infra-red gas analyser (IRGA) (ADC Bioscientific, Hoddesdon, Hertfordshire, UK) with a broad leaf chamber (6.25 cm^2 aperture) was used to measure net CO_2 assimilation and determine the leaf light compensation points (LCP) for each species. Eight healthy, fully expanded mid-canopy leaves from three plants, were used for the measurements. Measurements were made in the UoR glasshouses, where the plants were acclimatized for at least one hour prior to measurements being made. Data were collected between 10:00-16:00, when photosynthesis could expect to be occurring. The environmental conditions within the leaf cuvette were maintained at 24 ± 1°C, ambient RH (45 ± 5%) and ambient CO_2 concentration (420 ±25 ppm). The light intensity in the cuvette was increased in steps (0, 10, 20, 30, 50, 100, 150, 200, 250, 350, 500, 1000 µmol s^{-1} m^2). The increments were chosen to represent changes in light intensity that might be found within office environments, from darkness (0 µmol s^{-1} m^2), up to a maximum of 1000 µmol s^{-1} m^2 which might be found in conditions of bright sunlight. To allow time for the plant photosynthesis to adjust and stabilise, the light level was maintained for 5 minutes per setting.

The light response curves were generated using the model developed by Lobo et al., (2013) based on the equation by Prioul and Chartier (1977). The LCPs were determined at the point where the CO_2 assimilation was zero (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014) using the same model (Lobo et al., 2013). Data for *Sansevieria* is not included as the leaves were too thick to measure with the IRGA cuvette and for *Dypsis* the results were unreproducible.

In these experiments the leaf level LCPs were measured which do not account for the CO_2 emitted from the substrate thus LCPs on a potted plant basis are expected to be higher (Burchett, 2011). However, all experiments conducted in the chambers were carried out on a whole plant basis and therefore CO_2 emissions from the soil are included in the results assessing the carbon reduction potential.

3.2.3 Chamber experimental set up and environmental conditions

The equipment and calibration methods are described in detail in Chapter 2

3.2.3.1 Preparation for experimental chamber tests

To establish the test conditions to be used in the chamber experiments in order to represent real working environments, eight calibrated Hobo MX1102 data loggers (Onset Computer Corporation, Bourne, MA, USA) were used to measure the T_a (°C), RH (%), and CO_2 concentration (ppm) at four locations and two heights (1.8 m, 0.9 m), between 09:00 – 18:00 over ten days within two individual offices (volume approx. 62 m^3) and 1 meeting room located in the TSBE Centre. The light intensity was measured in the same locations using calibrated light meters; Testo 545 lux meter, (Testo Ltd, Hants, UK) and Skye PAR light meter (Skye instruments, Llandrindod Wells, Wales, UK). The CO_2 concentration (ppm) varied between 360 ppm for the empty rooms up to 2300 ppm for the meeting room with 20 occupants. The other parameters varied between; temperature 18 - 25^{o}C RH 30 - 70 % and light intensity 650 -1500 lux (approx. 10-30 µmol m^{-2} s^{-1}).

From the range of measurements recorded, the following parameters were selected as the target settings for use in the chamber experiments to represent room conditions of high occupancy and bright light: CO_2 concentration - 2000 ppm, light intensity - 1100 lux (15 µmol m^{-2} s^{-1}) and T_a 21 ^{o}C.

3.2.3.2 Chamber experiments

To determine the effectiveness of different plant species for removing CO_2 from the air within the sealed chamber, the method of measuring the change in CO_2 concentration over time from a known starting concentration was chosen as it has been established by previous researchers (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014; Oh, Jung, Seo, et al., 2011) as a reliable, effective method to estimate and compare the CO_2 removal rate of plants. Alternative methods include estimating the carbon sequestration potential of indoor plants by measuring the growth (change in dry mass) of the plant over time (S.V. Pennisi & van Iersel, 2012). This provides information on the net utilisation of CO_2 by plants over longer time scales, but it does not provide a measure of the short-term impact on IAQ. Measurements of the photosynthetic activity at leaf level have also been used to estimate the CO_2 removal rate for larger leaf areas and at room scale (Salvatori et al., 2020), but individual leaves can vary significantly depending on their age and position on a plant and leaf level measurements do not account for the CO_2 emissions from activity of the soil micro-organisms.

The purpose-made chambers (internal volume 0.79 m^3, dimensions 70.6cm x 93.0cm x 120.0 cm) comprised of two Perspex sides (top and removable front panel) and three walls and base made from insulated board. One, three or six plants were placed in the chamber in the positions shown in Figures 3.1 – 3.3. Initial experiments established that six plants per chamber was the maximum that the chambers could hold without overcrowding. After installing the plants within the chambers, the front panel was closed, and the edges completely sealed with two layers of 48mm adhesive, duct tape. A purpose-made, brushless fan (7.5 cm diameter) was included in each chamber to assist with air mixing which was turned on for 5 minutes after the introduction of the CO_2 gas. The chamber was vented with fresh air and the inside wiped and dried with absorbent paper between each experiment to remove any condensed water vapour. Initial monitoring for six hours showed the RH could increase to above 90% after the first hour for some species which is beyond the range of the sensors and could also affect the plant functioning and CO_2 removal, so the experiments were stopped after 1 hour.

CO_2 gas to a concentration of 2000 ppm ± 100 ppm was introduced into the chamber from a CO_2 gas cylinder (BOC UN1013). Three HOBO MX1102 data loggers, positioned at different locations (Figure 3.1) within each chamber and one additional sensor in the TSBE laboratory, recorded the T_a, RH and CO_2 concentration at 5-minute intervals. The air flow within the chambers was less than 0.2 $m^3\ s^{-1}$, measured with a Kestrel 4200 Air flow tracker (Nielsen -Kellerman Boothwyn, PA USA.

Figure 3.1

Figure 3.2

Figure 3.3

Figures 3.1- 3.3 Photographs showing experimental chamber set up with one, three and six plants per chamber.

Light intensity in the chambers was maintained at 1100 ± 100 lux (15 ± 2.5 µmol m^{-2} s^{-1}) using four electric ceiling lights in the room with 2 fluorescent bulbs per light (Philips Master TL5 HE 28 watt, 3000k warm white), two full spectrum electric lamps (Litepod, Internet Fusion Ltd., Kettering UK) located outside the front of the chamber and daylight from two windows. Light intensity within the chamber was measured in the horizontal plane at the start of the experiments with a Skye PAR light meter and a Testo 545 lux meter. The starting temperature (20 ± 2°C) and RH (50% ± 10%) within the chambers were representative of the room conditions at the time of testing. Air leakage from the chambers was measured by the same method with no plants in the chambers, with three replicates per chamber at the start and end of the course of all the experiments to check the leakage rate had not changed.

3.2.4 Data and Statistical Analysis

Environmental data (CO_2, T_a, RH) was downloaded and analysed using Excel.

Data from the three sensors within each chamber was used to calculate the mean CO_2 concentration (ppm) per chamber for 5-minute intervals for each experiment. The change in CO_2 concentration was calculated by subtracting the concentration after 1 hour from the starting concentration. In the enclosed chamber it is assumed that the reduction in CO_2 concentration above that of losses measured in the empty chamber is due to the effect of the plants and can be referred to as the CO_2 removal by the plant (Torpy, Irga, & Burchett, 2014). The volume and mass of CO_2 removed were calculated using:

Volume CO_2 removed = Change in CO_2 concentration (ppm) x Volume of chamber (m^3)

Mass of CO_2 removed was calculated from: Mass = Density of CO_2 x Volume CO_2 removed

Density of CO_2 at room temperature and pressure = 1.836 kg m^{-3}

Pillai's trace multivariate analysis of variance (MANOVA) was used to assess the overall effect of species and plant quantity on the mass of CO_2 removed. Separate one-way ANOVAs and post-hoc Scheffé tests were used to compare the effect of plant quantity of the CO_2 removal rate within the same species. Variance within the data was checked for normality assumptions and homogeneity (Levene's test).

3.3 Results

3.3.1 Plant parameters

The measured plant parameters are provided in Table 3.1 *Ficus* was the tallest plant followed by *Dypsis*, *Sansevieria* and *Calathea*. *Dypsis*, followed by *Asplenium* had the widest canopy whilst *Sansevieria* had the narrowest, most compact canopy.

Ficus had the largest leaf area followed by *Sansevieria, Dypsis, Epipremnum, Asplenium* and lastly *Calathea,* which had the smallest leaf area per plant. Approximations of the LADs showed that *Sansevieria* then *Ficus* had the highest leaf area density and *Epipremnum* had the lowest. *Ficus* had lots of small leaves distributed throughout the canopy whereas *Epipremnum* and *Calathea* had a small number of larger, widely spaced, leaves.

Plant species	**Height x diameter** (cm)	**Leaf area** (cm^2 $plant^{-1}$)	**Leaf Area Density (LAD)** (cm^2 cm^{-3} $plant^{-1}$)
Asplenium nidus	29 ± 1 x 40 ±2	2941 ± 192	0.08
Calathea majestica	40 ± 2 x 39 ± 2	1893 ± 95	0.04
Epipremnum aureum	14 ± 1 x 36 ± 3	4058 ± 165	0.03
Ficus benjamina	66 ± 1 x 34 ± 2	5803 ± 232	0.10
Dracaena fragrans	31 ± 2 x 34 ± 1	1219 ± 65	0.04
Sansevieria trifasciata	54 ± 1 x 29 ±2	5440 ± 291	0.15
Dypsis lutescens	60 ± 2 x 46 ± 4	4950 ± 210	0.05

Table 3.1: Plant dimensions of height and leaf area for each species ± SEM. Data are the means of 6 replicates per species, except for Ficus leaf area where data are the means of two replicates.

3.3.2 Leaf light compensation points

Plant species	**LCP µmol m^2 s^{-1}**
Asplenium nidus	11.1 ± 2.4
Calathea majestica	11.3 ± 3.5
Epipremnum aureum	8.3 ± 0.7
Ficus benjamina	11.1 ± 0.6
Dracaena fragrans	14.1 ± 1.2

Table 3.2: Light compensation points (LCPs) for five species of plant. LCPs are the mean of eight leaves per species from three plants ± SEM.

It was not possible to obtain an accurate light response curve for *Dypsis* but Torpy, Irga, & Burchett, (2014) previously determined an LCP (1.8 - 3.2 µmol m^2 s^{-1}) for this species and found it was comparable to that of *Ficus* measured in the same study. If we therefore assume in this study that the LCP of *Dypsis* is comparable to that of *Ficus*, we could expect *Dypsis* to have an LCP of approximately 11 µmol m^2 s^{-1}.

The measured LCPs for all plants ranged between 8.3 to 14.1 µmol m^2 s^{-1}, the lowest was for *Epipremnum* and the highest was for *Dracaena* respectively.

3.3.3 The effect of plant species and density on the removal of CO_2

The air leakage rate of the empty chambers was established (1.1 ± 0.1 %) and subtracted from the mass of CO_2 removed with plants in the chambers. The mass of CO_2 removed from the chambers by the plants ranged between 0.2 g h^{-1} $plant^{-1}$ reduction to an increase in CO_2 of 0.03 g h^{-1} $plant^{-1}$ depending on the quantity and species of plant (Figure 3.4). Using Pillai's trace MANOVA, a significant effect of plant species was found on the mass of CO_2 removed for all plant quantities, F(21,57)=5.52, $p<0.001$. The Scheffé post-hoc tests revealed that with one plant in the chamber, the CO_2 reduction was greater than the leakage rate of the empty chambers for all species except *Sansevieria, Dracaena and Calathea.* With three or six plants in the chamber the CO_2 reduction was greater than the leakage losses from the empty chamber, for all plants except *Sansevieria*.

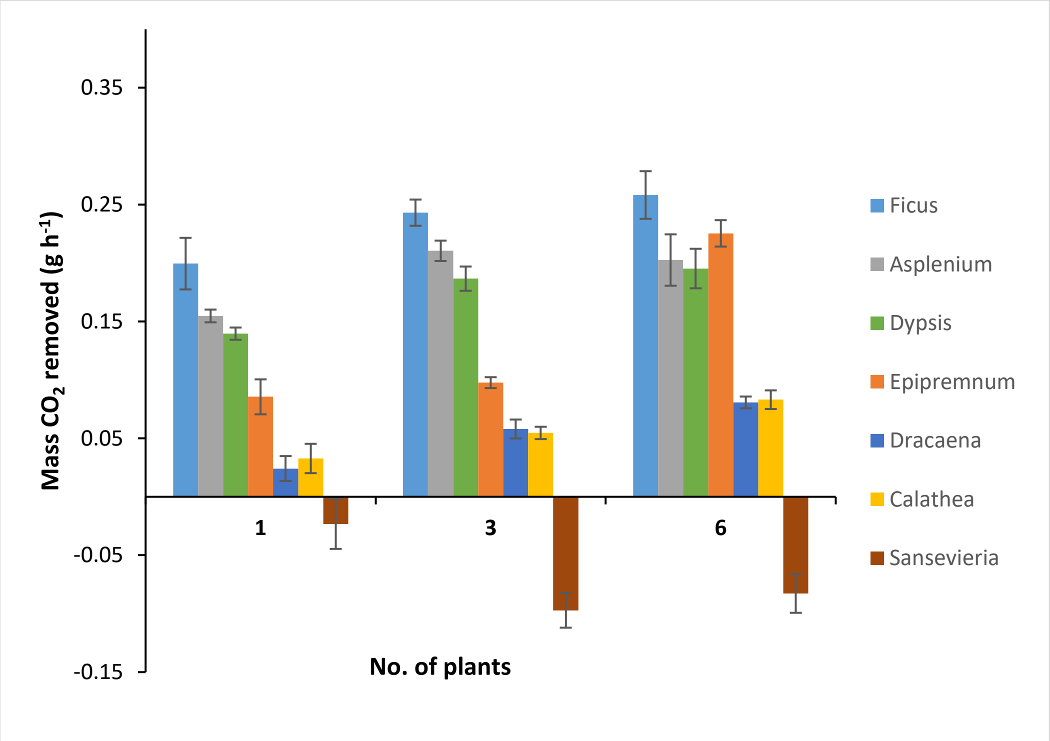


Figure 3.4: The effect of plant species and numbers on mass of CO_2 concentration within the experimental chamber over 1hour. Data are the means of 3 replicates (N=3) ± SEM. Data are corrected for chamber losses.

Ficus plants removed the highest mass of CO_2 across all plant quantities, but the p-values of 0.71 and 0.45 showed there was no signficant difference in the CO_2 removal rates between *Ficus, Asplenium* or *Dypsis*. With a single plant in the chamber *Ficus* removed approximately eight times the mass of CO_2 compared to *Dracaena,* which had the lowest removal rate of the C3 plants. *Sansevieria*, a CAM plant, added CO_2 to the chambers. The p-values of the post-hoc tests were greater than 0.05, which showed that with only one plant in the chamber there was no signficant difference between the change in mass of CO_2 with *Sansevieria*, *Dracaena* or *Calathea.* However with three and six plants in the chambers, the difference was signficant ($p<0.001$) with *Dracaena* and *Calathea* removing CO_2 whilst *Sansevieria* continued to add CO_2.

For all plants except *Sansevieria*, increasing the number of plants, and therefore the leaf area, in the chambers increased the total mass of CO_2 removed but the differences were not necessarily statisticially signficant. Separate ANOVAs for each plant species showed there was only a signficiant difference in the total mass of CO_2 removed by, *Epipremnum* where six plants removed signifciantly more CO_2 than 1 or 3 plants ($p<0.001$) and for *Dracaena* and *Calathea* where there was only a signifcant difference for the amount removed by six plants comapred to one ($p<0.05$).

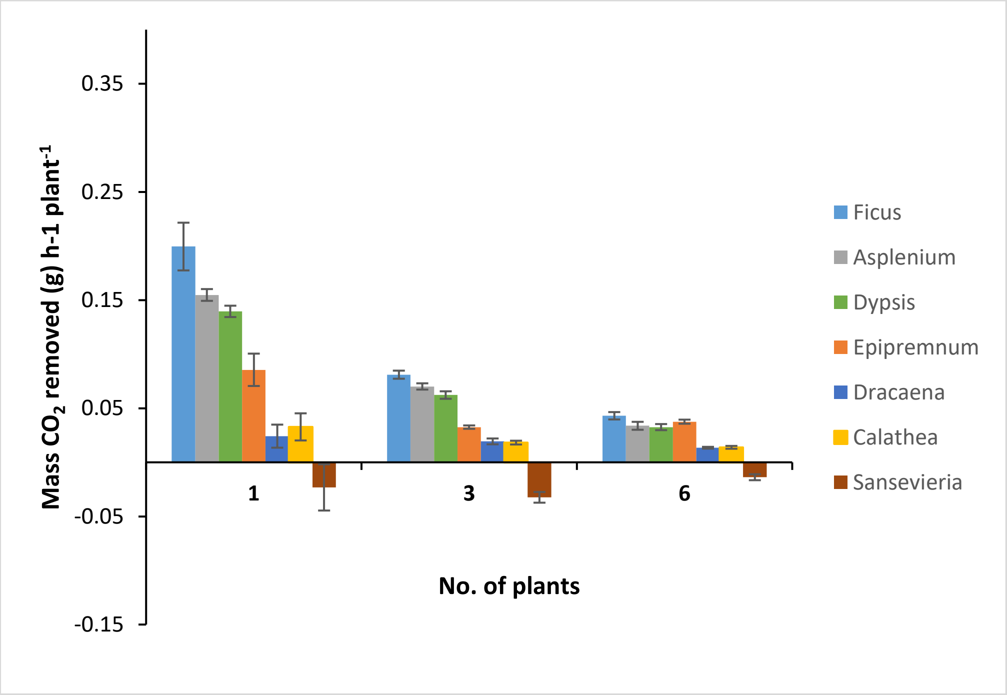


Figure 3.5: The effect of increasing plant numbers on reduction in CO2 g per plant, over 1 hour in the the experimental chambers. Data are the means of 3 replicates (N=3) ± SEM. Data are corrected for chamber losses.

As the number of plants in the chamber increased, the CO_2 removed per plant decreased for all species except *Sansevieria,* (Figure 3.5) but the extent of the effect varied with species. The removal rates decreased by between 44 -78% with six plants in the chamber compared to only one, and the ANOVAs and Scheffé post hoc tests showed that for all species except *Dracaena*, *Calathea* and *Sansevieria* the removal rates were signficiantly lower with six plants in the chamber compared to one plant (all $p<0.05$) but there was not always a signifcant difference between 1 and 3, or 3 and 6 plants.

The species with the highest CO_2 removal rates, *Ficus, Asplenium and Dypsis* were also those most affected by the increasing plant quantities. For *Dracaena*, *Calathea* and *Sansevieria,* the removal rate per plant was not signficantly affected by 3 or 6 plants in the chamber compared to 1 plant as all p-values were greater than 0.05.

3.3.4 The effect of leaf area on CO_2 removal rate

Since leaf and canopy size varied between species, to understand if the differences in CO_2 removal rate between species were due to differences in leaf area, the data was converted to mass of CO_2 removed per unit leaf area (Figure 3.6).

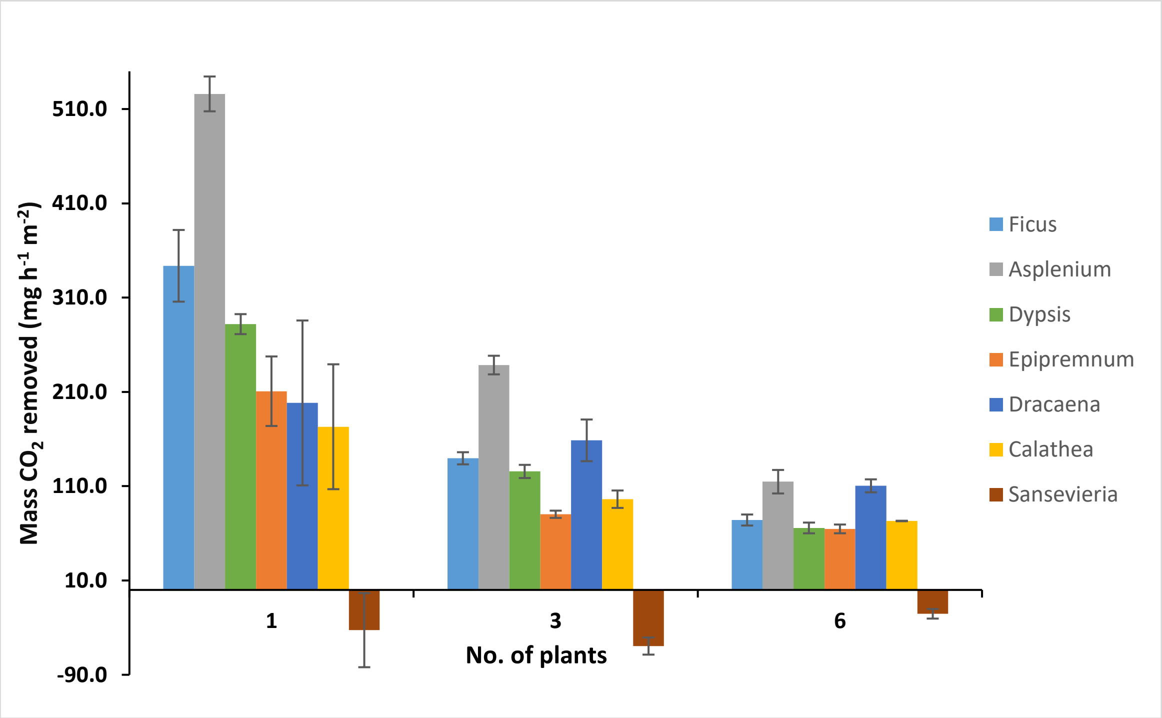


Figure 3.6: Comparison of the mass of CO_2 removed per m^2 of leaf area for different plant species, with differing quantities of plants in the chambers. Data are the mean of six replicates per treatment with associated SEM.

When comparing the CO_2 removal rate, per m^2 of leaf area for one plant, the mass of CO_2 removed varied between 65 mg h^{-1} m^{-2} for *Calathea* with six plants in the chamber, to 526 mg h^{-1} m^{-2} for *Asplenium* with one plant in the chamber. All plants performed best with only one plant in the chamber but there were few statistically significant differences between species. *Asplenium* had a significantly higher CO_2 removal rate per m^2 than *Sansevieria* ($p<0.001$), *Calathea* and *Dracaena* ($p<0.05$) with one plant in the chamber and it was higher than *Dyps*is ($p<0.05$) and *Sansevieria*

($p<0.001$) with six plants in the chamber. *Dracaena* followed by *Calathea* had the smallest leaf areas of all the plants tested and they also had the lowest removal rates per unit leaf area. *Ficus* had the largest leaf but the removal rate per unit area was only significantly higher than *Sansevieria*.

3.3.5 The correlation and regression analysis of LA and LAD with CO_2 removal

Pearson correlation coefficients between the plant parameters (leaf area, height, diameter, volume, LAD) and the removal rate of CO_2 for all C3 species, revealed there was only a significant positive relationship between leaf area and CO_2 removal, Pearson r = .71, ($p< 0.001$). *Sansevieria* was excluded as it was the only CAM plant and it added CO_2 rather than removed it and was considered an outlier in the dataset.

The regression showed there was a positive linear relationship between leaf area and mass (g) of CO_2 removed per hour, (R^2 =.518, F(1,16)=17.2, p =0.001). The fitted regression model was:
Mass CO_2 removed (g h^{-1}) = 0.074 + (5.66 x10^{-6} x Leaf area)

3.4 Discussion

3.4.1 Light requirements and compensation points

All plants measured had leaf LCPs below the light intensity provided in the chambers and could therefore be expected to photosynthesize (i.e. take up CO_2) to some extent. *Dracaena* had the highest leaf LCP, which equalled the lowest light intensity provided in the chamber experiments and could partially explain this species having the lowest CO_2 removal rate of all the C3 plants. *Epipremnum* had the lowest LCP and could therefore be expected to utilise light most efficiently and remove more CO_2 at lower light levels.

A small number of previous studies of indoor plants have reported a wide range of LCPs between 0.5 to 96 µmol m^2 s^{-1} (Gubb et al., 2018; Torpy, Zavattaro, & Irga, 2017; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) depending on plant species. The measurements in this study are therefore comparable with previous research. A wide range of physiological and environmental parameters can affect the LCP of plants and therefore explain the differences between studies, including the age of the plant and seasonal T_a (Ashton & Turner, 1979), acclimation conditions (Torpy, Irga, & Burchett, 2014) and stage of leaf formation (Kim et al., 2012). Through physiological and morphological changes plants can also adapt to varying light provisions which can increase or decrease light capture or utilisation. In response to lower light levels, reduced growth and decreased variegation (Kim et al., 2012), increased leaf area (Pennisi, Van Iersel, & Burnett, 2005), shedding of leaves (Steinitz et al., 1987), decreased chlorophyll content and thinner leaves (Kim et al., 2012) have been measured. In response to higher light intensity, adaptations such as narrower leaves and diminishing green colour have been observed (Kim et al., 2012). The changes depend on the species, the acclimatisation conditions and leaf age (Torpy, Irga, & Burchett, 2014; Kim et al., 2012).

3.4.2 CO_2 removal rates

The plant species had a significant effect on the reduction of CO_2 concentration within the chambers. With one plant in the chamber *Ficus, Asplenium and Dypsis* removed the greatest mass of CO_2, of 0.20, 0.15 and 0.14 g h^{-1} $plant^{-1}$ respectively. *Ficus* and *Dypsis* were the largest plants and had the greatest leaf areas, both parameters would aid photosynthesis and CO_2 removal; the greater leaf area would increase the area for light capture and the number of stomata available for gas exchange, and the increased height would raise the top of the plant canopy nearer to the overhead light source, thus increasing the light intensity. The dark green leaves of *Ficus benajamina* have also been shown to have a high chlorophyll content (Sevik, Karakas, & Karaca, 2013) which could increase light absorption and photosynthesis. When compared on a leaf area basis *Asplenium* had the highest CO_2 removal rate per m^2, showing the differences in CO_2 removal were due to more than just plant size, leaf area or colour. Previous research has shown that differences in stomatal size, density and speed of opening can influence gas exchange parameters between species (Kardiman & Ræbild, 2018b). *Asplenium* has been shown to have large stomata (Martin et al., 2004), which would increase the area for gas exchange and could help to explain the high CO_2 removal rate per unit leaf area.

Sansevieria emitted CO_2 during the experiments, which is explained by its reliance on crassulacean acid metabolism as part of photosynthesis (Lüttge, 2004), an adaptation which helps plants reduce water loss by closing their stomata during the day and opening them at night. Although this species also has large stomata they have been shown to be present in lower density compared to other species such as *Epipremnum* and *Calathea insginis* (Boraphech & Thiravetyan, 2015). *Sansevieria* could be an appropriate choice of species when CO_2 reduction in darkness is required or to balance CO_2 sequestration with C3 plants over longer time periods.

Although it is difficult to directly compare the CO_2 removal rates of individual plant species with other studies as many parameters of both the plants and the environmental conditions varied, the removal rates measured here for *Ficus* and *Dypsis* are comparable with those from a chamber study by Oh et al. (2011) who used light intensity of 1000 lux and a CO_2 concentration of 1000 ppm, and the rates for *Asplenium* are comparable with those measured in a sealed room by (Su & Lin, 2015), who used a CO_2 concentration of 2000 ppm and a light intensity of 513 lux. By contrast, in a study by Torpy, Irga, & Burchett, (2014), *Ficus* and *Dypsis* emitted CO_2 at a starting concentration of 1000ppm and low light (10 µmol m^2 s^{-1}) but had good removal rates at high light (350 µmol m^2 s^{-1}),

and in a study by Gubb et al., (2018) *Dracaena* emitted CO_2 at both low (10 µmol m^2 s^{-1}) and high (50 µmol m^2 s^{-1}) light. *Dracaena* has also been shown to be a facultative CAM plant and its possible this pathway may have been activated in this previous study (Burchett, 2011). Differences in the removal rates measured between studies could be due to the plant age, size, leaf areas and acclimation conditions. One key difference is the higher light intensity used in this study, which is known to increase photosynthesis, in addition the CO_2 concentration, temperature, RH and chamber size were all different.

The CO_2 uptake by plants within the chambers relies on the gas entering the plant's stomata by the process of diffusion and the rate of diffusion is directly proportional to the concentration gradient (Salisbury & Ross, 1992). The rate of diffusion would therefore be expected to decrease as the CO_2 concentration within the chamber decreased and extrapolation of results from short timescale chamber studies may therefore lead to overestimation of the CO_2 uptake by plants at room-scale over longer time periods.

Increasing the density of plants within the chamber reduced the CO_2 removal efficiency of all C3 plant species but the greatest impact was on *Ficus, Asplenium and Dypsis.* These plants had the highest CO_2 removal rates and were the tallest and widest plants which would cause shading as the plant density increased, reducing the light available for photosynthesis leading to reduced gas exchange. In addition, increasing the plant density leads to changes in the microclimate in the air space between the plants such as reducing air movement, increasing RH and reducing the CO_2, which can increase the boundary layer thickness above the leaf leading to reduced gas exchange (Runkle, 2016). Differences in leaf size, shape and morphology between and within species, can both affect the microclimate, and also be affected by it (Schuepp, 1993).

3.5 Conclusion

This chapter determined the LCPs and investigated the effect of plant density and species on the CO_2 removal rates of seven different indoor plant species to assess their potential for reducing CO_2 concentrations within indoor environments.

The study showed that the plant species and plant density had a significant effect on the change in CO_2 concentration within the sealed chambers. All C3 plants reduced the CO_2 concentration at the light intensity used whereas *Sansevieria* increased it. This confirms the importance of species selection when choosing indoor plants for potential IAQ improvements from CO_2 removal at a room scale. The results also showed that as the plant density increased within a space of restricted volume, the efficiency of the CO_2 removal per plant decreased. This finding shows that the spacing of plants and the shape, size and density of the canopies are important considerations when using multiple plants in arrangements for IAQ improvements.

The results of these studies show that the amount of CO_2 uptake by one plant is very small in comparison to the CO_2 emitted by one human. One person in an office environment typically emits approximately 32g of CO_2 per hour through respiration (Persily & de Jonge, 2017) and based on the rates of CO_2 uptake measured during these experiments, the following estimated number of plants would be required to mitigate all of this CO_2 at 1100 lux (15 μmol m^2 s^{-1}): *Ficus* - 160, *Asplenium* - 213, *Dypsis* - 229, *Epipremnum* - 356, *Calathea* – 1067 and *Dracaena* – 1600.

This number of plants could be reduced by using higher light intensities and in studies by Torpy et al. (2014), an estimated 206 *Dypsis lutescens* plants would be required at a light intensity of 350 μmol m^2 s^{-1} (25,000 lx) and Gubb et al. (2018), estimated 150 *Hedera helix* or *Spathiphyllum wallisii* plants would be required at a light intensity of 300 μmol m^2 s^{-1} (22,000 lx).

Based on these results for the plants species tested, *Ficus benjamina* and *Asplenium nidus* had the highest CO_2 removal rates and the greatest potential for reducing the CO_2 concentration at a room scale. These plants were therefore selected for use in experiments to determine the effectiveness of plants for CO_2 reduction at a room scale in Chapter 4.

Chapter 4

Room scale studies of the impact of plants on the reduction of CO_2 concentrations

4.1 Introduction

Chapter 3 investigated the impact of different species of indoor plant on reducing the CO_2 concentration within small-scale sealed chambers and determined the response of the plants to different light intensities and planting densities. This chapter is focussed on the impact of the plants on reducing CO_2 concentrations at room-scale.

High CO_2 concentrations in indoor environments are of concern as they can adversely impact occupant health, productivity and satisfaction with the IEQ (Jafari et al., 2015; Erdmann & Apte, 2004; Seppanen, Fisk, & Mendell, 1999). Relatively small increases in CO_2 levels have been shown to reduce cognitive performance (Allen et al., 2016; Satish et al., 2012) and one study found that a 400-ppm increase in indoor CO_2 levels was associated with a 21% decrease in performance of office workers on a cognitive task (Allen et al., 2016). Raised CO_2 concentrations can also reduce people's perceptions of IAQ and increase SBS symptoms such as headaches and tiredness, and these can show large seasonal differences (Mizoue et al., 2004; Seppanen, Fisk, & Mendell, 1999).

To maintain CO_2 concentrations in office environments within best practice guidelines, indoor air is typically exchanged with fresh air from outside through the use of natural ventilation or mechanical systems (ASHRAE, 2013; CIBSE, 2006a, 2011). However, mechanical ventilation systems can be energy-intensive and expensive (Chenari et al., 2016; Luengas et al., 2015) and natural ventilation may be restricted when cold weather, noise or pollution outdoors make it undesirable for occupants to open windows or vents. The potential for indoor plants to reduce CO_2 concentrations has been demonstrated on a laboratory scale in Chapter 3 and other studies (Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) and although the CO_2 uptake by plants is small in comparison to the amount exhaled by humans, in poorly ventilated rooms small reductions in CO_2 concentrations could benefit the occupants.

Very few studies have verified the findings of the impact of indoor plants on CO_2 levels from chamber scale at room scale (Torpy, Zavattaro, & Irga, 2017), although the conditions can be very different. As outlined in Chapter 1, one of the major differences affecting the CO_2 concentration on a room scale is the air exchange, which occurs through ventilation and infiltration through openings arounds doors and windows and through small gaps or cracks in the building envelope.

In an office-based study, Pennisi & van Iersel (2012), showed that most species of indoor plants tested, sequestered carbon as shown by the change in dry mass of the plant over a period of 12 months but this does not provide a measure of the short-term impact of plants on IAQ and therefore the potential benefits for the occupants. Based on the results of chamber scale tests, Torpy, Zavattaro, & Irga, (2017), demonstrated CO_2 removal rates of 4.1-5.5 g h^{-1} for *Chlorophytum* species in a sealed, office-sized test room. Other studies have investigated the impact of indoor plants on CO_2 concentrations at room scale (Pamonpol, Areerob, & Prueksakorn, 2020; Treesubsuntorn & Thiravetyan, 2018; Tudiwer & Korjenic, 2017; Tarran, Torpy, & Burchett, 2007) with mixed results and important parameters which influence the concentration of CO_2 in the room between these studies also varied, such as occupancy and ventilation rate,, or the factors which affect CO_2 uptake by the plant such as light intensity, have often not been considered. A study of two comparable, unoccupied classrooms showed a 3.5% faster reduction in CO_2 concentration in a classroom where a green wall was installed, but the plants were not specified, and the CO_2 was only measured in the summertime although measurements of RH and Ta showed seasonal variation (Tudiwer & Korjenic, 2017). Another study reported a 35% higher CO_2 reduction rate in a sealed room with a wall of potted *Asplenium nidus* plants, compared to the room with no plants but the study was not repeated, and the air infiltration rate was not measured (Su & Lin, 2015). Other studies have found no impact from plants on indoor CO_2 concentrations (Wood et al., 2006) and other researchers have proposed that an impractically high number of indoor plants would be required to make significant IAQ improvements at a room scale based on laboratory scale studies (Cummings & Waring, 2019; Gubb et al., 2018; Llewellyn & Dixon, 2011).

When assessing the potential of plants to lower CO_2 concentrations within indoor environments, it is important to take into account the air exchange rate of the room, the properties of the plant and the seasonal variation in environmental conditions. There is therefore a need to determine the impact of indoor plants on the reduction of $CO_{2,}$ concentrations in real indoor environments, to maximize the benefits for the health and well-being of building occupants.

The objectives of this chapter were therefore:

- To investigate the variability of the ACH of different naturally ventilated offices
- To determine if measurements of plant CO_2 removal rates made in small scale sealed chambers can be verified at room-scale
- To determine how indoor plants affect the reduction of CO_2 concentration within real office environments during the working day, in different seasons, taking into account the ACHs.

4.2 Materials and methods

A series of experiments were conducted in a total of five offices, situated within two naturally ventilated buildings of different types of construction within the UoR between November 2019 - February 2021. The ACHs and change in mass and volume of CO_2 concentration were measured in the offices with and without plants. To eliminate the effect of occupants on the CO_2 concentration and the air exchange all experiments were conducted when the rooms were unoccupied.

4.2.1 The experimental test offices and buildings

4.2.1.1 Building 1 – Offices 1 and 2

Initial experiments (October–December 2018) were carried out in two adjacent cellular, offices situated within the TSBE Centre on the top floor of the JJ Thomson building on the University of Reading Whiteknights campus. The three-storey building was constructed in the 1950's and has a framed structure with traditional brick faced elevations and pitched roof. The office interiors were refurbished approximately 3 years prior to the test date. The Centre houses research students, academic and administrative staff and each office typically houses 1-2 members of staff.

Figure 4.1: South facing elevation Building 1

The offices, located on the south facing side of the building were of comparable size; floor areas 20.7 m^2 and 18.9 m$^{2.}$ and volumes 62.5 m^3 and 57.7 m^3 for Office 1 and 2 respectively. Experiments were conducted over weekends when those spaces were unoccupied. The offices rely on natural ventilation, with two openable windows (each measuring 135 x 258 cm), which were kept closed during the experiments. The three internal doors were kept closed during the experiments and one layer of 48mm masking tape was applied between the door and the frame before the start of each experiment to reduce the size of the large gaps which existed between the doors and the frames.

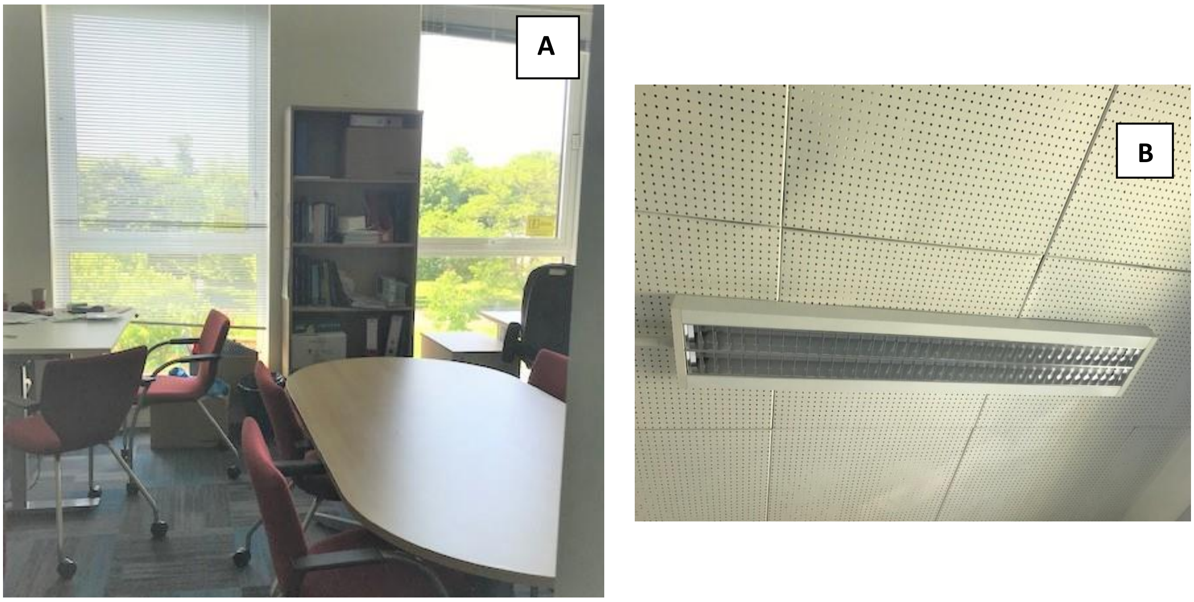


Figure 4.2: Office 1 Interior A = Full height windows B= Electric ceiling light and perforated ceiling

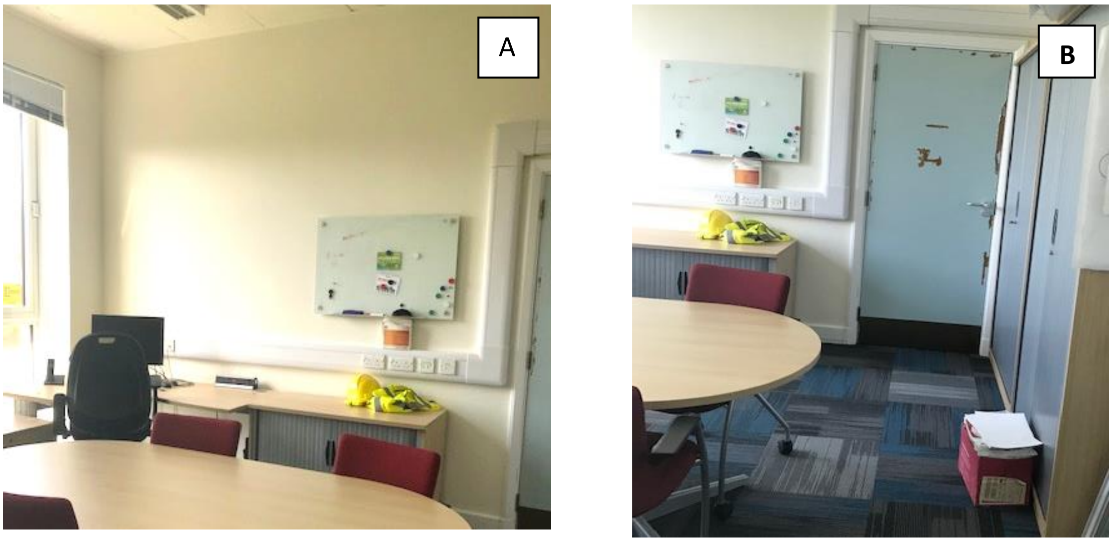


Figure 4.3 : Office 1 Interior. A = Desk area B = internal door before sealing with tape

The normal office environmental conditions when occupied, measured between 09:00 – 18:00 over ten days without any plants in the room were: CO_2 concentration 360 -1500 ppm, T_a 18 - 25^{0}C, RH 30 - 90 % and light intensity 650 -1800 lux (approx. 10-30 µmol m^{-2} s^{-1}). During the experiments lighting was maintained above 1000 lux with light from the four electric ceiling lights each containing two Sylva Ecoline bulbs (FHO 20w T5 840) (Sylvania, Newhaven, UK) in addition to sunlight through the windows (Figure 4.2). The rooms are heated by radiant heaters, supplied from a centralised district heating system, concealed behind a perforated ceiling (Figure 4.2 B). The heating was set to out of hours regime during the experimental test period (see 4.2.1.2).

As the mechanisms for natural ventilation were kept closed during the experiments, the air exchange was mainly due to infiltration. Results provided in section 4.3.1 showed a high variability in the ACHs and air temperature in these offices despite attempts to reduce this by sealing the gaps around the doors and conducting measurements during periods of calm weather when the building was unoccupied. Due to this high variability after the initial experiments during autumn 2018 no further testing was conducted in these offices.

4.2.1.2 Building 2 – Offices 1, 2 and 3

Building 2 (Chancellor's building) is a two-storey, prefabricated, modular building constructed in 2015 on the University of Reading, Whiteknights campus. The building provides teaching rooms on the ground floor and offices for academic and administrative staff on the first floor. The building was selected as it was of modern construction and it was anticipated the offices would have lower and less variable ACHs than Building 1, to meet the UK Building Regulations (2010) requirements.

Three offices were used for testing between December 2019 – February 2021. Offices 1 and 3 were located on the north facing side of the building and Office 2 was on the south facing side of the building (Figures 4.4 -4.6). Offices 1 and 2 were used for experiments during winter 2019, but due to limited office availability, spring and summer experiments were continued only in Office 1. During winter 2021, Office 3 which was directly adjacent to office 1, was available for use as a control office with no plants. Each office typically houses one academic member of staff, but all experiments were conducted when the offices were unoccupied and the single internal door in each office was kept closed. Office 1 had one internal glazed partition (270 cm x 106cm) with an internal blind which was kept closed. The office dimensions were; Office 1 (Total floor area =10.5 m^2) Volume = 28.3 m^3, Office 2 (Total floor area =11.3 m^2) Volume = 30.4 m^3, and Office 3 (Total floor area = 11.35 m^2) Volume = 30.6 m^3.

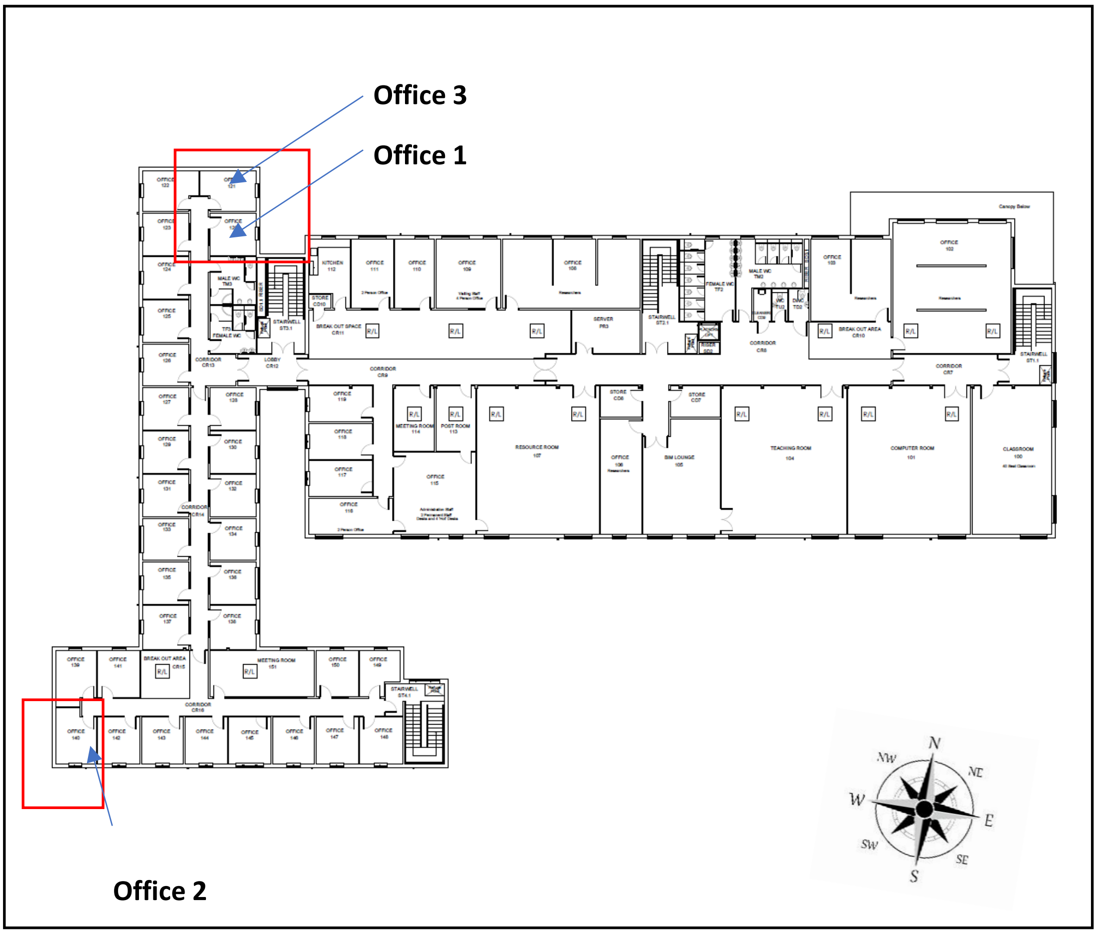
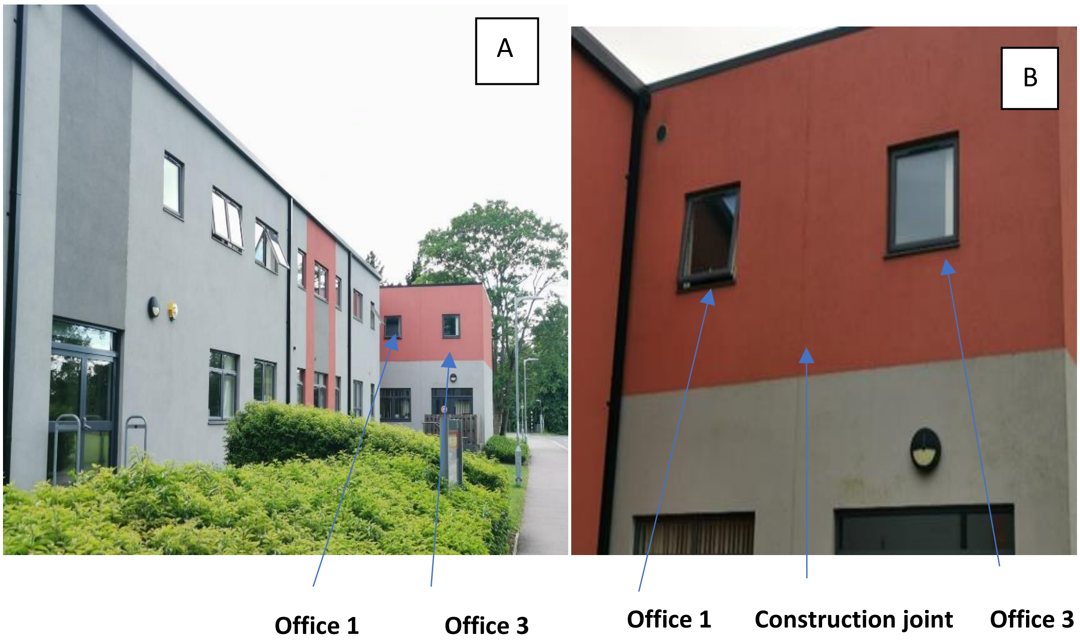


Figure 4.4: Building 2 first floor plan showing location of offices 1 , 2 and 3



Figures 4.5 A and B: North facing elevation Building 2

Figure 4.6: Front entrance and east facing elevation Building 2

Figure 4.7: South facing elevation Building 2

The office interiors are constructed of suspended ceiling grid and tiles, with painted walls and carpet tiled floor covering. The heating within the building is delivered from electric wall panel heaters and is controlled by a central Building Management System linked to several thermostats positioned throughout the building. The heating system is enabled to maintain the T_a above 19°C during normal occupancy times (08:00-18:00 Monday to Friday), which is described here as *working day* heating regime, and above 12°C outside of these hours (overnight, weekends and closure periods) and this is described as *out of hours* regime. Experiments throughout 2018 - 2019 were conducted during weekends and holidays with “out of hours” heating and experiments during winter 2021 were conducted when the building was unoccupied but with “working day” heating. Ventilation in each office is supplied by one openable window (104 cm x 96 cm) with a user-controlled trickle vent, both of which were kept closed during the experiments.

4.2.3 Measurement of environmental parameters

To provide an understanding of the cross-sectional and longitudinal profile of the T_a, CO_2 and RH distribution within the offices, eight calibrated, Hobo MX1102 data loggers (Onset Computer Corporation, Bourne, MA, USA) were used to measure the T_a (°C), RH (%), and CO_2 concentration (ppm) at four locations and two heights (1.8 m, 0.9 m) within office 1 between 09:00 – 17:30 (Full details of the sensors are provided in Chapter 2). From this data, it was decided that three sensors would be used at representative locations within the study offices shown in Figure 4.11. An additional HOBO MX1102 data logger recorded the IAQ conditions in the corridor outside Offices 1 and 3 during winter 2021. The environmental conditions within the offices were monitored over one week prior to the experiments to establish the normal office conditions. The CO_2 concentration varied between 400 -530 ppm for the empty rooms and other parameters varied between T_a (17 - 23^{o}C), RH (40 - 60 %) and light intensity 400- 1100 lx (approx. 8-15 μmol m^{-2} s^{-1}).

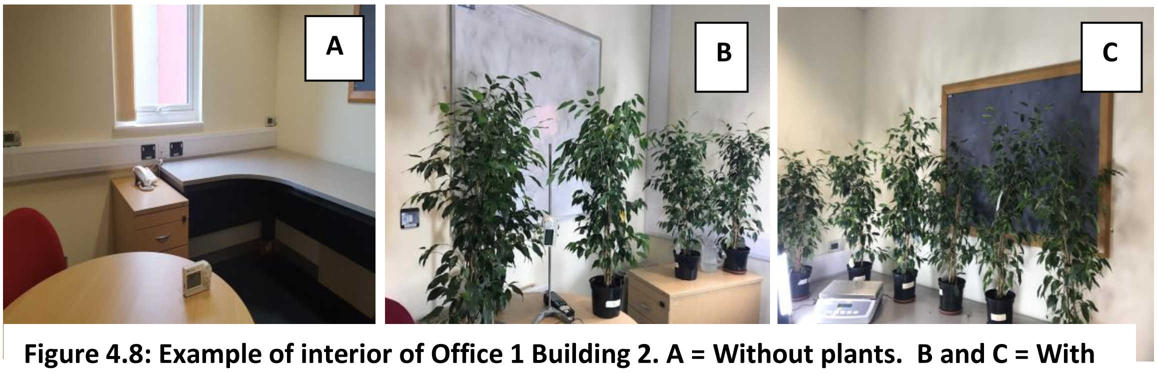


Figure 4.8: Example of interior of Office 1 Building 2. A = Without plants. B and C = With *Ficus benjamina* plants

Figure 4.9 : Interior of Office 2 Building 2 with *Asplenium nidus* plants

Figure 4.10: Office interiors - A,B,C = Interior of Office 3 - no plants. D= Internal corridor

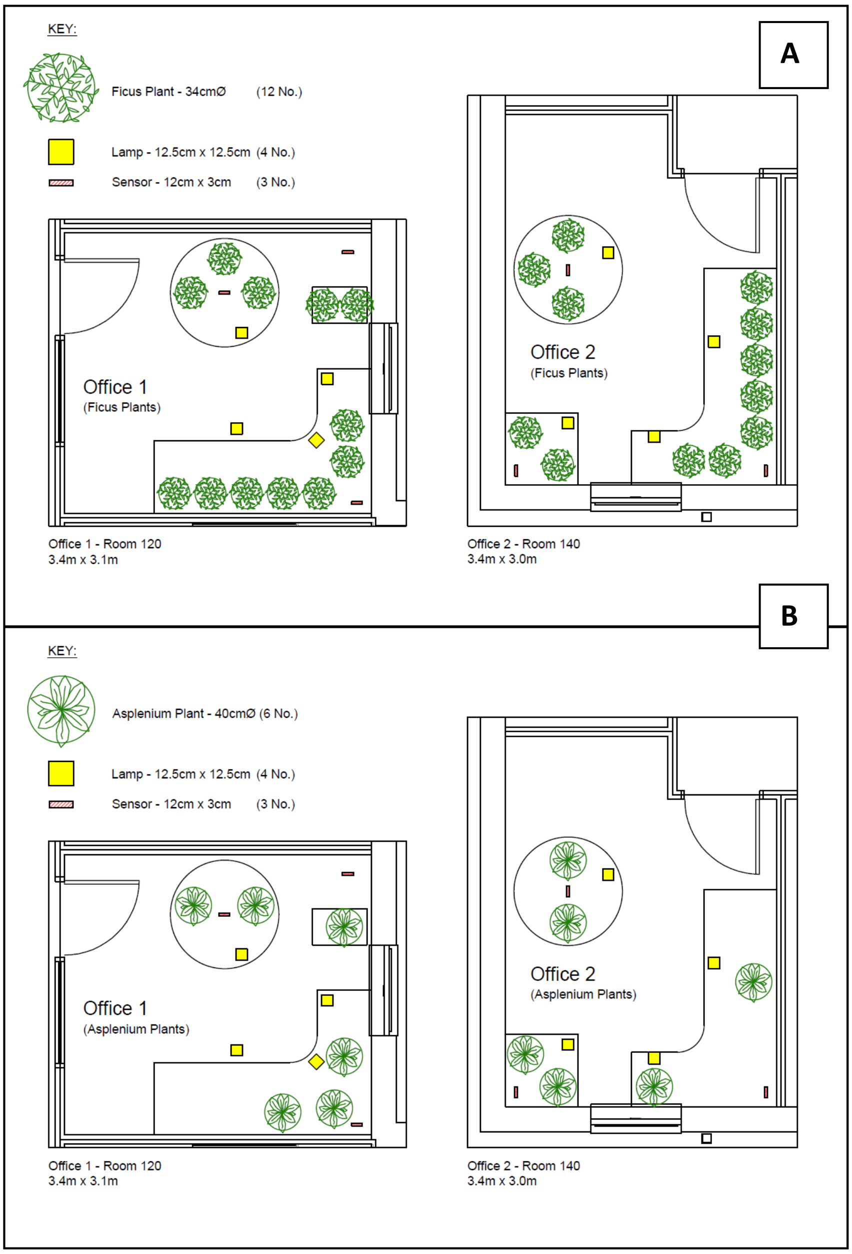


Figure 4.11: Plans showing location of plants, extra lights and sensors in offices 1 and 2. A= with *Ficus* plants. B= with *Asplenium* plants

Light intensity measurements were taken at multiple positions in each office, using a Testo 545 lux meter (Testo Ltd, Hants, UK) and Skye PAR light meter (Skye instruments, Llandrindod Wells, Wales, UK) at the start of each experiment. Normal lighting in each office is provided by two electric panel ceiling lights, each containing two Sylva Ecoline bulbs (FHO 20w, T5 840, 4000 k) (Sylvania, Newhaven, UK). To increase the light intensity to a background level of 1000 lux (~15 µmol m^{-2} s^{-1}) additional light was supplied during the experiments from four electric lamps (Litepod, Internet Fusion Ltd., Kettering, UK). The electric lights were on between 09:30 and 17:30

each day. Details of the lamp positions and plants are provided in Figure 4.11. Where possible all experiments were set to start at 09:30 and were considered complete after 24 hours.

Outdoor weather conditions can affect the ACH and indoor climate conditions within buildings (Nguyen, Schwartz, & Dockery, 2014). The outdoor temperature and RH were taken from five-minute recordings, at the University of Reading, Meteorological office observation site (1.1 km east of the test offices). Preparatory studies identified that wind strength and direction, and rain significantly influenced the ACH and RH within the rooms. To reduce the impact of this, the outdoor weather forecasts and conditions were monitored, and experiments were conducted on calm, dry days and data was not included if the weather conditions changed suddenly such as strong winds or rain occurred during the experiments. The outdoor pressure varied between 98-104 kPa across all the experiments but tended to be consistent during the plant and no plant days within each season. The sensors were calibrated against the outdoor CO_2 concentration at the start of each experiment.

4.2.4 Measurement of the ACH and change in CO_2 concentration.

To measure the ACH of the offices, the concentration decay method was selected with CO_2 as the tracer gas. It is appropriate for a single zone, it is low cost - allowing multiple repetitions to be carried out, basic equipment is required, relative values of CO_2 concentration can be compared over different experiments and it has been successfully used by previous researchers (Persily, 2016; Charlesworth, 1988). This also enabled the change in the rate of CO_2 reduction with and without plants to be measured at the same time. The constant tracer gas injection method and constant concentration methods are alternative tracer gas methods which were considered but not selected as they require more advanced equipment and expertise, and are more difficult to control (Charlesworth, 1988). Air tightness measurements can be made through air pressurization tests and used to determine the ACHs (Awbi, 2003; Charlesworth, 1988), but these were not considered appropriate as they do not measure the change in CO_2 concentration.

CO_2 gas was introduced into the office from a CO_2 gas cylinder (BOC UN1013). The air within the office was mixed using an electric, 16-inch pedestal standing fan (Beldray, Gloucester, UK) for approximately 10 minutes until all the sensors were reading comparable CO_2 concentrations of approximately 2000 ppm. The CO_2 concentration was recorded at 5-minute intervals for approximately 24 hours (as described in 4.2.3). During winter and summer 2019 all experiments were repeated a minimum of three times with and without plants in the offices on days of calm weather, this was increased to six repeats in spring 2019 and winter 2021.

4.2.5 Plant material

Ficus benjamina and *Asplenium nidus* plants were selected for testing in the Winter 2019 experiments as they had the highest rates of CO_2 uptake based on the findings of the chamber experiments in Chapter 3 and previous research (Su & Lin, 2015). By the time of the winter 2021 experiments, the findings from Chapter 5 had revealed that new *Epipremnum* plants of a larger size had a high transpiration rate in addition to the low LCP measured in Chapter 3, so these were selected for the winter 2021 experiments.

The plants and methods used are described in detail in Chapter 2.

Plant species	Height x diameter (cm)	Leaf area (cm^2 plant^{-1})	Metabolism
Asplenium nidus	29 ± 1 x 40 ±2	2941 ± 462	C3
Epipremnum aureum	68 ± 1 x 32 ± 1	5797 ± 627	C3
Ficus benjamina	66 ± 1 x 34 ± 2	5803 ± 232	C3

Table 4.1: Plant dimensions of height and leaf area for each species ± SEM. Data are the means of six replicates per species, except for Ficus leaf area where data are the means of two replicates.

Six replicate plants of *Asplenium,* or *Epipremnum* or twelve *Ficus* plants were installed in the offices in the positions shown in figure 4.11 (*Epipremnum* was located as per *Asplenium* in Office 1), to test the impact of the plants on the “With Plant” days. The plants were watered 1 h prior to the start of the experiments to maintain the substrate moisture content (SMC) at a starting level of 45% as described in Chapter 2.

4.2.6 Data and Statistical Analysis

The mean CO_2 concentration (ppm), T_a (°C) and % RH were determined using the 5-minute measurements from the three sensors, for each experiment. To allow time for the air within the room to stabilise after introducing and mixing the CO_2, the starting time for data analysis was between 09:30 – 10:00 when the CO_2 concentration had settled to approximately 2000 ppm. Data was analysed for the following time periods after the start time: 1 hour to provide a comparison with the majority of literature studies, 3.5 hours to represent the working period until lunchtime and 7.5 hours to represent a full day in the office.

Data was checked for normality and homogeneity of variance (Levene's test). A one-way ANOVA with post-hoc Tukey's honest significance difference test (Tukey HSD) was used to compare the change in CO_2 concentration in the offices between each treatment when the sample groups were of equal size (No plants, *Ficus* plants or *Asplenium* plants) and post-hoc Scheffé multiple comparison tests were used when the group sizes were uneven (Seasonal comparisons of winter, spring and summer). When there were only two groups for comparison (Plants or No plants) two-sided paired comparison t-tests were used.

The difference between the indoor and out temperature difference (ΔT) was calculated at 1 h, 3.5 h and 7.5 h for each experiment (N = 54). Pearson correlation coefficients (r) were calculated to assess the strength of the association between ΔT and the ACH rates.

4.2.7 Theoretical basis of Calculation of Air Change Rate (ACH)

When using the concentration decay method with CO_2 as the tracer gas to determine the ACH of each office, the rate of change in the CO_2 concentration over time in an enclosed space, is equal to the amount of CO_2 gas leaving (or removed) from the space, minus the amount of gas entering or being generated within the space. Assuming perfect mixing and no density changes through the space, the rate of change in concentration can be represented by the mass balance equation (4.1):

$$\mathbf{V}dc/dt = \mathbf{G} + \mathbf{Q}(c_e - c) \qquad (4.1)$$ (Awbi, 2003)

V= effective volume of enclosure (m^3)
Q = air volume flow rate through the enclosure (m^3 s^{-1})
c_e = external concentration of tracer gas at time *t*
c = internal concentration of tracer gas at time *t*
G = generation rate of tracer gas within the enclosure (m^3 s^{-1})
Assuming there is no incidental source of tracer gas and ignoring the concentration of tracer gas in the external air, equation 4.1 can be rearranged to

$$Vdc/dt = -Qc \qquad (4.2)$$

Assuming a constant air flow and integrating equation 4.2 provides

$$\int_{c0}^{c} \frac{dc}{c} = -\frac{Q}{V}\int_{0}^{t} dt \qquad (4.3)$$

Which can be rearranged to:

$\ln c - \ln c_0 = -(Q/V)t$ (4.4)

Equation (4.4) can be written as

$C = C_0 e^{-[Q/V]t}$ (4.5)

Q/V = Air Changes per unit time (4.6)

Plotting the natural logarithm (ln) of concentration (c) against time (t) gives a straight-line graph of negative slope Q/V, which is the number of air changes per unit of time (air exchange rate) or the Air Changes per Hour (ACH) (CIBSE, 2011; Awbi, 2003). For simplicity the term ACH is used to describe both the air exchange rate and the air change rate per hour in this thesis. To assess how the air change rates varied over different time periods during the day, the logarithm (ln) of the CO_2 concentration recorded at 5-minute intervals, was plotted over 1 h, 3.5 h and 7.5 h to and the comparative ACHs derived.

4.3 Results

4.3.1 Building 1 - Autumn 2018

		Building 1 Office 1	**Building 1 Office 2**
Treatment	**Time after start (h)**	**Air exchange rate ACH**	**Air exchange rate ACH**
No plants	1	0.528 (± 0.263)	0.638 (± 0.263)
	3.5	0.305 (± 0.08)	0.360 (± 0.07)
	7.5	0.245 (± 0.091)	0.251 (± 0.16)
***Ficus* Plants**	1	0.646 (± 0.1 0)	0.350 (± 0.05)
	3.5	0.309 (± 0.033)	0.295 (± 0.029)
	7.5	0.203 (± 0.011)	0.136 (± 0.018)

Table 4.2: Air change rates determined for Offices 1 and 2 in Building 1. Data are the Mean of three repeats ± SEM.

The ACHs within both offices in Building 1 varied considerably across all test days (Table 4.2). Within Office 1 during the days with No Plants, the full range of individual air change rates varied by 86% between 0.169 - 1.171 ACH, for the first hour. On the days with plants in the office, the air change rates varied by 45% between 0.882 - 0.477 ACH. In Office 2, on the days with No plants in the office the ACH varied by 79%, between 0.257 - 1.221 during the first hour and by 46%, between 0.241- 0.405 ACH on the days with plants in the office. The air temperatures within the offices also varied considerably between 17.4 - 26.2°C across all the test days. Due to this high variability further experiments were not carried out in these offices.

4.3.2 Building 2 – Seasonal measurements (2019-2021)

4.3.2.1 Winter 2019

Winter 2019: Building 2 - Office 1						
Treatment	**Time after start (h)**	**Indoor Temp. (°C)**	**Outdoor Temp (°C)**	**Air exchange rate (ACH)**	**Reduction in volume of CO_2 ($L\ h^{-1}$)**	**Reduction in mass of CO_2 ($g\ h^{-1}$)**
No plants	1	18.77 (± 0.45)	9.26 (± 0.85)	0.177 (± 0.003)	9.61 (± 0.98)	17.65 (± 1.80)
	3.5	18.56 (± 0.39)	10.32 (± 0.48)	0.162 (± 0.005)	7.30 (± 0.27)	13.40 (± 0.49)
	7.5	18.89 (± 0.57)	8.92 (± 0.54)	0.134 (± 0.004)	4.94 (± 0.13)	9.07 (± 0.23)
Ficus	1	19.43 (± 0.58)	8.00 (± 0.62)	0.237 (±0.007)	11.83 (± 0.41)	21.73 (± 0.74)
	3.5	19.73 (± 0.85)	9.33 (± 0.98)	0.204 (±0.011)	8.44 (± 0.18)	15.50 (± 0.33)
	7.5	18.56 (± 0.71)	7.33 (± 1.60)	0.161 (±0.017)	5.28 (± 0.15)	9.69 (± 0.27)
Asplenium	1	16.55 (± 0.41)	3.50 (± 0.85)	0.194 (±0.024)	10.37 (± 1.10)	19.04 (± 2.02)
	3.5	17.39 (± 0.91)	8.50 (± 2.09)	0.168 (±0.019)	7.39 (± 0.70)	13.56 (± 1.29)
	7.5	17.391 (± 0.10)	2.83 (± 0.76)	0.132 (±0.020)	4.94 (±0.44)	9.08 (± 0.80)

Table 4.3: Comparison of the air change rates, and the change in the rate of reduction in the volume and mass of CO_2 over time in Office 1 with and without plants, during winter 2019. Data are the mean of three repeat test days (N=3) per treatment (± SEM). The time after the start represent 1 h = 10.00 am, 3.5 h =1.30 pm and 7.5 h= 5.30 pm approximately.

Winter 2019: Building 2 - Office 2						
Treatment	**Time (h)**	**Indoor Temp. (°C)**	**Outdoor Temp (°C)**	**ACH**	**Reduction in volume of CO_2 (L h^{-1})**	**Reduction in mass of CO_2 (g h^{-1})**
No Plants	1	21.02 (± 0.67)	9.26 (± 0.85)	0.243 (±0.05)	13.08 (± 1.74)	24.02 (± 3.19)
	3.5	20.85 (± 0.43)	10.32 (± 0.48)	0.188 (±0.01)	8.35 (± 0.34)	15.32 (± 0.63)
	7.5	20.75 (± 0.61)	8.92 (± 0.54)	0.131 (±0.008)	5.16 (± 0.10)	9.47 (±0.18)
Ficus	1	17.10 (± 0.92)	3.50 (± 0.85)	0.201 (±0.021)	10.74 (± 0.82)	19.72 (± 1.51)
	3.5	18.28 (±1.33)	8.50 (± 2.09)	0.147 (±0.009)	7.17 (± 0.22)	13.16 (± 0.41)
	7.5	18.17 (± 0.87)	2.83 (± 0.76)	0.106 (±0.002)	4.74 (± 0.08)	8.70 (± 0.15)
Asplenium	1	19.12 (± 0.85)	8.00 (± 0.62)	0.258 (±0.02)	13.20 (± 2.34)	24.23 (± 4.30)
	3.5	20.11 (±1.14)	9.33 (± 0.98)	0.212 (±0.01)	8.57 (± 0.41)	15.74 (± 0.75)
	7.5	20.20 (± 0.94)	7.33 (± 1.60)	0.145 (±0.026)	5.20 (± 0.40)	9.55 (± 0.74)

Table 4.4: Comparison of the air change rates, and the change in the rate of reduction in the volume and mass of CO_2 over time in Office 2 with and without plants, during winter 2019. Data are the mean of three repeat test days (N=3) per treatment (± SEM). The time after the start represent 1 h = 10.00am, 3.5 h =1.30 pm and 7.5 h= 5.30 pm approximately.

During winter 2019, the average daytime indoor T_a within Office 1 (Table 4.3) across all test days ranged between 16.6°C – 19.7°C and were significantly lower than the temperatures within Office 2 (Table 4.4) for all time periods and all test days (all $p<0.05$), where the temperatures ranged between 17.1 -21.0°C. The ANOVA and post-hoc Tukey's test showed there was no significant difference in temperature in either Office 1 or Office 2, on the days with either *Ficus* or *Asplenium* plants compared to the days without plants as all p-values were greater than 0.05. It was significantly cooler in Office 1 on the test days with *Asplenium* plants compared to the days with *Ficus* plants ($p<0.05$) but there was no significant difference in the temperatures in Office 2.

The T_a within both offices remained reasonably stable throughout the day and was consistently higher than outdoors, which ranged between 2.8-10.3°C. The higher indoor temperatures, despite there being low levels of heating during the test period, show the offices are well insulated. The

Pearson correlation coefficient had a p-value of 0.89, which shows there was no correlation between the indoor and outdoor temperature difference (ΔT) and the ACH of the offices.

The mean rate of reduction in the mass of CO_2 gradually slowed during the day for all experiments (Tables 4.3 and 4.4) as the concentration of CO_2 within the offices reduced (Figure 4.12).

Tables 4.3 and 4.4 show that the highest rates of CO_2 reduction occurred during the first hour and these varied from 24.2 g h^{-1} with *Asplenium* plants in Office 2, to 17.7 g h^{-1} with No plants in Office 1. When compared over 7.5 hours, the mean rates reduced to 8.7 - 9.7 g h^{-1} across all experiments and both offices.

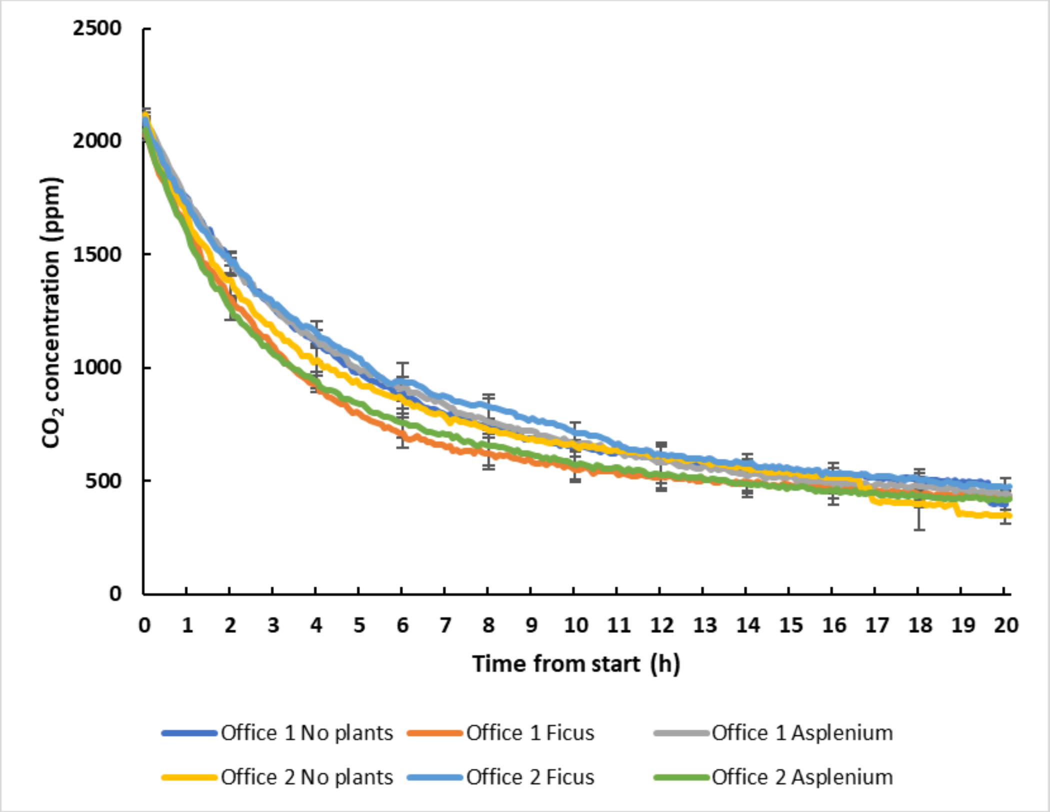


Figure 4.12: CO_2 Concentration decay curves for offices 1 and 2 with and without plants during winter 2019. Data are the mean of 3 repeats per office, per treatment ± SEM.

The ANOVAs and post hoc Tukey's tests showed there were no significant differences in the change of CO_2 concentration in Office 1 or Office 2 with either *Ficus* or *Asplenium* plants in the office compared to the same office without plants, over any time period, as all p-values were greater than 0.05.

With no plants in the offices, Office 1 had a consistently lower mean ACH than Office 2 but the paired t-tests showed the difference was only significantly different after 7.5 hours (two tailed, $p<0.05$).

4.3.2.1 Spring 2019

The T_a was warmer during the springtime experiments compared to the winter measurements for both indoors and outdoors. The average daytime T_a remained reasonably stable throughout the day and within Office 1 they ranged between 19.4°C – 24.7°C, whilst outdoor temperatures ranged between 11.8 -19.5 °C (Table 4.5). The paired t-tests showed the air temperature was significantly warmer during the test days with *Ficus* plants in the office compared to the days without plants for all time periods (all $p<0.001$).

		Spring 2019: Building 2 - Office 1				
Treatment	**Time (h)**	**Indoor Temp. (°C)**	**Outdoor Temp. (°C)**	**Air change rate ACH**	**Reduction in volume of CO_2 (L h^{-1})**	**Reduction in mass of CO_2 (g h^{-1})**
No Plants	1	19.36 (± 0.14)	11.78 (± 0.99)	0.179	9.57 (±1.03)	17.56 (± 1.89)
	3.5	19.38 (± 0.13)	13.66 (± 1.81)	0.171	7.37 (± 0.53)	13.54 (± 0.97)
	7.5	19.76 (± 0.03)	11.51 (± 1.96)	0.134	4.97 (± 0.18)	9.13 (± 0.34)
***Ficus* plants**	1	21.95 (± 0.59)	17.42 (± 0.22)	0.223	11.47 (± 0.63)	21.06 (± 1.15)
	3.5	23.20 (± 0.59)	19.50 (± 0.51)	0.206	8.39 (± 0.43)	15.41 (± 0.78)
	7.5	24.66 (± 0.53)	17.46 (± 0.77)	0.156	5.14 (± 0.02)	9.44 (± 0.04)

Table 4.5: Comparison of the air change rates and reduction in volume and mass of CO_2 within office 1, with and without Ficus plants during spring (April) 2019. Data are the mean of six days of repeat tests per treatment (N=6) (± SEM).

The mean ACHs within Office 1 were lower on the days without plants (0.179 - 0.134 ACH) compared to the days with *Ficus* plants in the office (0.223 - 0.156 ACH) but due to the variation across all of the test days, the results of the paired t-tests showed there was no significant difference in the ACH within Office 1 on the days with or without plants, over any time period (1 h, 3.5 h, 7.5 h) since all p-values were greater than 0.05.

The Pearson correlation coefficient, r = -.473, ($p < 0.01$), shows there was a significant negative association between the indoor and outdoor temperature difference (ΔT) and the ACH of the offices, as the difference in temperature increased, the ACH decreased.

The mean rate of reduction of the mass of CO_2 over the first hour on the days with plants in the office, was 21.1 g h^{-1} and 17.1 g h^{-1} on the days without plants, and higher over 3.5 hours but when compared over the 7.5-hour day, the mean hourly rates of reduction were comparable with and without plants, 9.4 -9.1 g h^{-1} respectively. However, the p-values for all paired t-tests were greater than 0.05, showing there was no significant difference in the rate of reduction of the mass of CO_2 concentration with *Ficus* plants in the office compared to the office without plants for any time periods.

4.3.2.2 Summer 2019

		Summer 2019: Building 2 - Office 1				
Treatment	**Time (h)**	**Room Temp. (°C)**	**Outdoor Temp (°C)**	**ACH**	**Reduction in volume of CO_2 ($L\ h^{-1}$)**	**Reduction in mass of CO_2 ($g\ h^{-1}$)**
No Plants	1	21.79 (± 0.16)	18.40 (± 0.55)	0.249 (± 0.085)	12.40 (± 3.56)	22.77 (± 0.46)
	3.5	22.21 (± 0.20)	20.04 (± 1.30)	0.212 (± 0.059)	8.24 (± 1.40)	15.13 (±0.23)
	7.5	22.51 (± 0.19)	18.88 (± 0.87)	0.132 (± 0.032)	5.00 (± 0.34)	9.17 (± 0.07)
***Ficus* plants**	1	24.27 (± 0.46)	16.25 (± 0.14)	0.266 (± 0.018)	13.52 (±0.77)	24.82 (± 1.41)
	3.5	25.96 (± 0.45)	20.00 (± 0.29)	0.271 (± 0.010)	10.07 (± 0.12)	18.49 (± 0.22)
	7.5	27.02 (± 0.44)	18.5 (± 0.58)	0.219 (± 0.009)	6.19 (± 0.12)	11.37 (± 0.22)

Table 4.6: Comparison of the air change rates, and the change in the rate of reduction in the volume and mass of CO_2 over time in Office 1 with and without *Ficus* plants, during summer 2019. Data are the mean of three repeat test days (N=3) per treatment (± SEM). The time after the start represent 1 h = 10.00am, 3.5 h =1.30 pm and 7.5 h= 5.30 pm approximately.

The summer indoor and outdoor mean air temperatures were higher than winter and spring. The mean daytime temperatures within the office, during the days without plants were fairly stable over the 7.5-hour day and ranged between 21.8 - 22.5 °C (Table 4.6). On the test days with plants in the office, the indoor temperatures increased during the day and Paired t-tests showed the mean air temperature was significantly higher after 3.5 and 7.5 hours (all $p<0.05$) on the days with plants compared to the days without plants.

Whilst the mean ACHs within Office 1 appeared to be slightly higher on the days with *Ficus* plants over all the time periods, 1h, 3.5h and 7.5 h (0.266- 0.219 ACH) compared to the days without plants in the office (0.249 - 0.132 ACH) (Table 4.6), the results of the paired t-tests showed there was no significant difference over any time period, (all $p > 0.05$). The p-value of the Pearson correlation coefficient was0.52, which shows there was no significant correlation between the indoor and outdoor temperature difference (ΔT) and the ACH within Office 1.

The mean rate of reduction of the mass of CO_2 was typically between 9-24% higher on the days with plants compared to days without plants over all time periods. The rates varied from 24.8 - 22.8 g h^{-1} over the first hour for the days with and without plants respectively. Over the 7.5-hour day, the rates of reduction were 11.4 g h^{-1}, with plants compared to 9.2 g h^{-1}, on the days without plants . However, we cannot be confident that the differences were due to the presence of the plants rather than natural variation in the ACHs, as the p-values for the paired t-tests were greater than 0.05, which showed there was no significant difference in the rate of reduction in the mass of CO_2 concentration with *Ficus* plants in the office compared to the office without plants for any time periods).

4.3.2.3 Seasonal variation of ACH rate in Office 1 during 2019

Although the mean ACHs in Office 1, were higher in summer compared to winter and spring, both with and without plants (Tables 4.3, 4.5 and 4.6), the p-values of the ANOVA and post hoc Scheffé multiple comparison tests were all greater than 0.05, which showed there were no significant differences in the mean ACHs of Office 1 between winter, spring or summer 2019 over 1 hour, 3.5 hours or 7.5 hours

Post-hoc power analysis were conducted using G*power version 3.1.9.7 (Faul et al. 2009) on the ANOVA and paired test results for the groups Plants or No Plants for each season. The results revealed that based on the paired test results of the ACHs after 7.5 h, with a significance criterion of $\alpha = 0.05$ and an effect size determined from the results for each group, the power of the tests was between 21 - 46% which is low compared to Cohens criteria of 80%. This means there may have been differences between the groups which were not picked up due to the small sample sizes. It is recommended the number of repeat tests is increased in future studies.

4.3.2.4 Winter 2021 - Offices 1 and 3

Treatment	Time (h)	Winter 2021: Building 2 - Office 1				
		Room Temp. (°C)	Outdoor Temp	ACH	Reduction in volume of CO_2 (L h^{-1})	Reduction in mass of CO_2 (g h^{-1})
No Plants	1	19.50 (± 0.49)	6.68 (± 1.50)	0.178 (± 0.015)	8.72 (± 0.78)	16.02 (± 1.44)
	3.5	20.67 (± 0.61)	7.57 (± 1.46)	0.159 (± 0.013)	6.53 (± 0.55)	11.99 (± 1.02)
	7.5	21.02 (± 0.82)	6.83 (± 1.21)	0.124 (± 0.009)	4.43 (± 0.36)	8.14 (± 0.67)
Epipremnum **(Plant test days)**	1	19.70 (± 0.31)	4.95 (± 1.96)	0.229 (± 0.024)	11.98 (± 0.79)	22.00 (± 1.45)
	3.5	20.96 (± 0.18)	7.13 (± 1.47)	0.197 (± 0.015)	8.16 (± 0.34)	14.98 (± 0.62)
	7.5	21.91 (± 0.30)	5.68 (± 1.59)	0.149 (± 0.006)	5.19 (± 0.21)	9.53 (± 0.39)

Table 4.7: Comparison of the air change rates, and rate of reduction in the volume and mass of CO_2 over time in Office 1 with and without Epipremnum plants, during winter 2021. Data are the mean of five repeat test days (N=5) per treatment (± SEM).

Treatment	Time (h)	Winter 2021: Building 2 - Office 3				
		Room Temp. (°C)	Outdoor Temp	ACH	Reduction in volume of CO_2 (L h^{-1})	Reduction in mass of CO_2 (g h^{-1})
No Plants	1	20.18 (± 0.31)	6.68 (± 1.50)	0.093 (± 0.013)	5.95 (± 0.55)	10.93 (± 1.02)
	3.5	20.96 (± 0.18)	7.57 (± 1.46)	0.074 (± 0.007)	4.27 (± 0.20)	7.84 (± 0.37)
	7.5	20.91 (± 0.30)	6.83 (± 1.21)	0.069 (± 0.007)	3.50 (± 0.13)	6.43 (±0.24)
No plants (Control on Plant test days)	1	19.76 (± 0.50)	4.95 (± 1.96)	0.074 (± 0.006)	5.23 (± 0.48)	9.60 (± 0.89)
	3.5	19.94 (± 0.54)	7.13 (± 1.47)	0.067 (± 0.004)	4.13 (± 0.21)	7.59 (± 0.38)
	7.5	20.32 (± 0.65)	5.68 (± 1.59)	0.068 (± 0.003)	3.64 (± 0.11)	6.68 (± 0.20)

Table 4.8: Comparison of the air change rates, and rate of reduction in the volume and mass of CO_2 over time in Office 3 with and without six Epipremnum plants, during winter 2021. Data are the mean of five repeat test days (N=5) per treatment (± SEM).

The mean indoor T_a within Office 1 were comparable on the “No plant” and the “Plant” test days ranging between 19.5-21.0 °C and 19.7-21.9 °C respectively between 09:30-17:30. Within Office 3 the T_a’s were also consistent across all test days ranging between 19.8 -20.3 °C and 20.2- 0.9 °C on the “No Plant” and “Plant” test days respectively. There were no significant differences in T_a between the two offices or between different test days as the p-values of the paired t-tests were greater than 0.05. The mean outdoor T_a over the test days ranged between 4.5 -7.1 °C.

The mean ACH in Office 1 ranged between 0.178 - 0.124 ACH on the “No plant” days and were lower than on the days with plants in the office, where the ACHs ranged between 0.229 - 0.149 ACH. In Office 3, the ACHs were lower than Office 1 and ranged between 0.093-0.069 ACH on the “No plant” test days and 0.074 -0.068 ACH on the “Plant” test days. The results of the two-sided paired t-tests showed the mean ACH and the rate of reduction in the mass of CO_2 were significantly higher in Office 1 compared to Office 3 on both “Plant” and “No Plant” test days at 1h, 3.5 h and 7.5 h (all $p<0.05$). The mean CO_2 concentration decay curves show the rate of reduction in CO_2 concentration was faster in Office 1 compared to Office 3, but comparable within the same office on the “Plant” and “No Plant” test days (Figure 4.13).

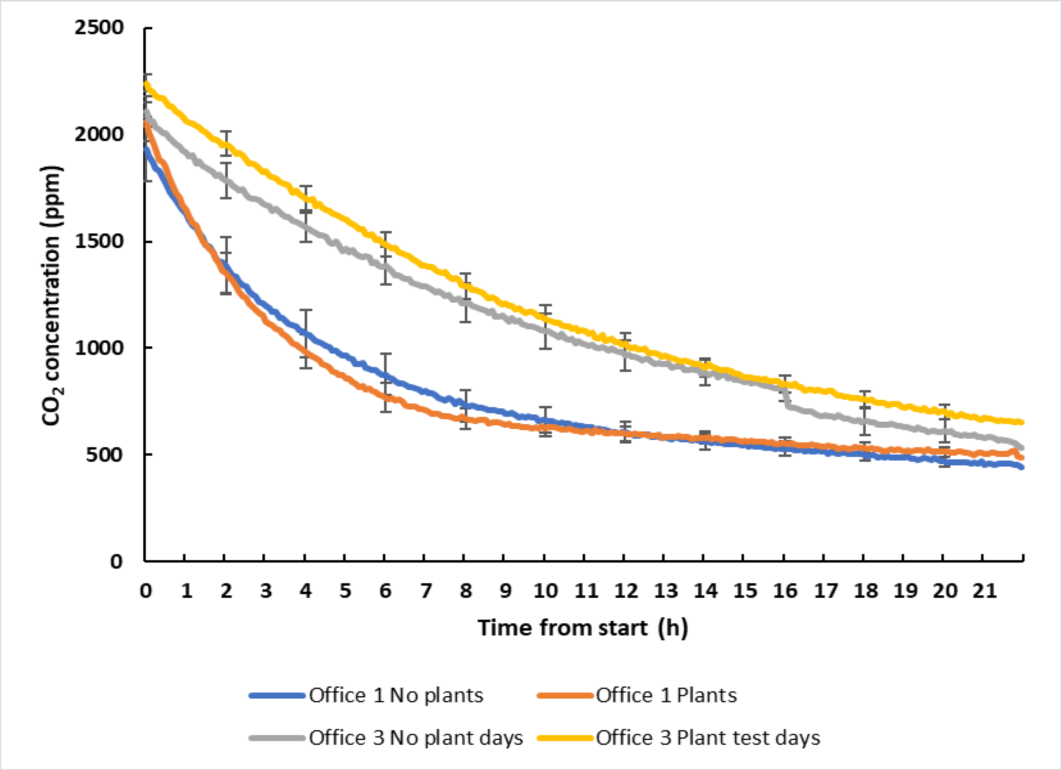


Figure 4.13: CO_2 Concentration decay curves in offices 1 and 3 during winter season 2. On No plant test days there were no plants in either office, on Plant test days, Office 1 had *Epipremnum* plants in and Office 3 had No plants. Data are the mean of five repeats ± SEM.

When comparing the mass of CO_2 removed within the same office, the paired t-tests showed there was no significant differences within Office 1, on the test days with plants compared to the days without plants after 1 h or 3.5 h, but over 7.5 hours, a significantly higher mass of CO_2 was removed on the days with plants present compared to the days without, $p<0.05$. There were no significant differences within Office 3.

To determine if the higher quantity of CO_2 removed in Office 1 on the Plant days was greater than could have been expected to be attributed to normal variation in the ACH, the mass of CO_2 removed from Office 1 was normalised by subtracting the reductions measured in Office 3 (the control office without plants). The normalised differences determined in Office 1 on the individual days with and without plants were then compared. The p-values of the paired t-tests were; 1h ($p= 0.17$), 3.5h ($p= 0.13$) or 7.5 h ($p=.0.52$) which show the differences were not statistically significant and we cannot therefore be confident that the higher mean mass of CO_2 removed after 7.5 hours was due to the plants and not the natural variation in the ACHs between the test days.

4.3.2.1 Uncertainty associated with results

The air flow in naturally ventilated rooms is subject to variation depending on the outdoor weather conditions, which can vary significantly. Whilst attempts were made to conduct the experiments on calm weather days the results may have been different under different weather conditions, in different months or years. Access to the offices was limited in these experiments, but for a more detailed understanding of the ACH in each room the experiments should be repeated multiple times over much longer time periods.

Changes in air pressure can affect the ACH (Awbi, 2003) and although these were checked to avoid testing on days with large pressure differences, pressure differences were not analysed in detail and may have influenced the ACHs.

For the seasonal comparisons of the CO_2 reduction in the offices the same *Ficus* plants were used and these would therefore have matured between January and September.

4.4 Discussion

The air exchange rate is the main factor which governs the rate at which CO_2 is removed from a room. In these experiments the air exchange was mainly due to infiltration as the sources of natural ventilation were closed. The ACHs varied between buildings, between different offices in the same building and on different days, both with and without plants present. In order to have a statistically significant impact on the rate of CO_2 reduction, the indoor plants need to remove more CO_2 than could occur by this normal variation alone. In these experiments the presence of either 12 *Ficus* plants, six *Asplenium* plants or six *Epipremnum* plants did not have a significant impact on the ACHs above that of the normal day to day variation in the offices.

In Building 1 which was an older, framed building, constructed in the 1950's with traditional brick faced elevations and pitched roof, the mean ACH of the offices was two and a half times that measured in Building 2, a prefabricated, modular building constructed in 2015. This shows that the type of construction has a significant impact on the ACH of the rooms and in these experiments, a greater effect on the rate of CO_2 reduction than the indoor plants. Although only a small number of ACH measurements were made during these experiments, the impact of building age and construction type on ACHs is established in other studies (Persily, 1989).

Within Building 2, the rate of CO_2 reduction determined for three offices of comparable dimensions, also differed significantly, even though measures were taken to reduce the impact of variables such as strong winds and occupant behaviour. There were no significant differences between any of the offices, in the same season, on the days with plants compared to without plants. Therefore, it seems that the position of the office within the building and the fit out of the individual office had a greater impact on the rate of CO_2 reduction than the presence of plants.

Air exchange through infiltration depends on the size of the openings such as gaps and cracks around the windows, doors, walls and ceilings and the factors which drive the air flow through the openings such as the indoor and outdoor pressure and temperature differences and the wind direction and speed (Awbi, 2003; British Standards, 1991). In Building 1, the form of construction including perforated office ceiling tiles (Figure 4.2B) and larger, older style windows would provide larger areas for infiltration compared to the recently constructed, more airtight Building 2 in addition to the buildings having different geometry and locations. In Building 2, Office 1 and Office 2 were located on different sides of the building (Figure 4.4) and would therefore be subjected to differing effects of wind pressure, direction and speed; varying amounts of sunlight and differences within the interior such as a larger gap under the door in Office 2. All of these would contribute to differences in the infiltration rates (Persily, 2016). There were also differences in the ACHs between Office 1 and Office 3 although the rooms were directly adjacent to each other in Building 2, and therefore subject to the same outdoor weather conditions. Office 3 had an internal glazed partition and closer inspection of the internal fit out revealed ducting within the ceiling void and a construction joint between the modular units within Office 1, which would increase the infiltration gaps compared to Office 3.

From 2010, the UK Building regulations Part (UK Government, 2010) require new buildings to have a supply rate of fresh air of 10 l s^{-1} per person or 36,000 l h^{-1} (36 m^3 h^{-1}) per person on a whole building scale. Assuming each office has only one occupant, the recommended ACHs for Office 1,2 and 3 in Building 1, in order to meet these requirements would be 1.272, 1.183 and 1.176 ACH respectively. Using equation (4.6) to calculate the air supply rate (ACH x room volume), we find that the highest mean air supply rate for Building 2, across all experiments was 7.7 m^3 h^{-1}, showing that when the offices are operated with the windows, door and trickle vents closed and relying on infiltration only, the air supply rate is considerably below the recommended requirement of 36 m^3 h^{-1}. If operated in this state, these would be unhealthy offices for occupants to work in due to the build-up of bioeffluents, moisture and carbon dioxide, all of which are indoor pollutants (Fisk, Mirer, & Mendell, 2009).

A study in Portugal, which used the tracer gas method to measure the ACHs due to infiltration in a naturally ventilated office building, showed the ACHs varied between 0.13 – 0.66 ACHs (or 1.6 - 7.6 m^3 h^{-1}) for multiple cellular offices (typically about 12 m^2) across different seasons (Afonso, 2015). In a study of university offices in China, ACHs from 0.101 ACH to 2.633 ACH, were determined for a closed office in winter to an air-conditioned office with the window open, in summertime (Zhang et al., 2015). By comparison the ACHs measured in this study for the offices in Building 2 without plants, ranged between 0.067 ACH for office 3 in winter to 0.249 ACH for Office 1 in summertime over the first hour. The results for Office 1 are therefore comparable to the low end of the other studies but Office 3 in this study has an extremely low ACH when operated with the windows, trickle vent and door closed.

Previous indoor plant research has shown that CO_2 uptake by indoor plants is dependent on the provision of adequate light (Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) and that typically the highest rates of uptake during the day are between 11:00 – 13:00, although this varies with species (Sevik et al., 2018). As all plants used in these experiments were C3 plants, it would be expected that that the rate of CO_2 reduction would be greatest between 09:00 -18:00 and there would be an overall net increase of CO_2 in the dark periods. As the CO_2 assimilation rates of the plants were not directly measured during the experiments, it is possible that these differences occurred but were masked by the raised CO_2 concentrations and variation in the ACHs of the offices or alternatively, the plants were not assimilating CO_2. The findings from this study, contrast with the study by Su & Lin, (2015) where the rate of reduction of CO_2 concentration was approximately three times higher with *Asplenium nidus* plants compared to without plants, but they used a greater number of small plants (189 plant in 10 cm pots) and did not account for the infiltration rate. Another study measured a 3.5% higher rate of CO_2 reduction in a classroom with a green wall compared to a classroom without (Tudiwer & Korjenic, 2017), but it is difficult to compare these results directly as the plant species are not specified and although the classrooms were adjacent, they had an ACH of three, which would be subject to variation and may be greater than 3.5% difference.

When comparing the ACHs after 1h, 3.5h and 7.5 h, the ACHs and rate of reduction in CO_2 concentration was highest at the start of the experiments, and slowly decreased over time. This can be explained by the gas moving by diffusion through the air gaps and cracks and the rate of diffusion is directly proportional to the concentration gradient, hence as the CO_2 concentration reduces so does the rate of diffusion. .When comparing Office 1 in Building 2 over winter, spring and summer, no significant differences were found in the seasonal ACHs or the rates of CO_2 reduction (g h^{-1}) with or without plants.. A previous study found higher ACHs in offices during the summer compared to the winter and the ACHS were also higher on the south facing side of the building (Zhang et al., 2015), although in Zhang's study the ventilation conditions were also changed between summer and winter in their study. Higher ACHs in the summer could be due to higher outdoor air pressure creating a larger pressure difference, which would increase the infiltration rate (Awbi, 2003). Although there were no significant differences in our experiments, it could be anticipated that indoor plants would have a higher uptake of CO_2 during the summer months in response to warmer temperatures and longer hours of daylight and higher light intensity. Differences in the T_a and RH across the seasons are investigated in detail in Chapter 6.

One of the objectives of this study was to determine if the measurements of plant CO_2 uptake rates made in small scale sealed chambers could be verified at room scale. From the chamber experiments in Chapter 3, the highest mean CO_2 removal rate measured for *Ficus* plants was 0.2 g $h^{-1}plant^{-1}$. Applying this rate to the offices used in these experiments, it could be expected that 12 *Ficus* plants would remove approximately 2.4 g CO_2 h^{-1}. The mean mass of CO_2 removed from office 1 in Building 2 during 2019 without any plants, during the first hour varied between 17.6-22.8 g CO_2 h^{-1} and the standard deviation (SD) varied between 2.4-3.1 g CO_2 h^{-1} across all experiments. On the days with 12 plants the mass of CO_2 removed varied between 21.7-24.8 g CO_2 h^{-1} and the SD varied from 1.3-2.8 g CO_2 h^{-1}. It is possible the plants were contributing to the typically higher mass of CO_2 removed on the days with plants in the offices but the day-to-day variation in the ACHs is greater than the amount the plants would contribute. Thus, the CO_2 uptake rates measured in the small-scale chambers in Chapter 3 were not verified with statistical confidence in these experiments.

In a typical office environment one person adds approximately 32g of CO_2 per hour through respiration (Persily & de Jonge, 2017), and the twelve *Ficus* plants could therefore remove approximately 8% of the CO_2 released by one person, and one plant would remove less than 1%.

Apart from variation in ACHs, the CO_2 uptake of the plants may also have been influenced by differences in the environmental conditions for example, light intensity is known to be a main factor affecting plant photosynthesis (Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) and whilst additional lamps were added to increase the general light intensity to 1000 lux, there was some unavoidable variation in amounts of natural sunlight within the offices caused by cloud cover and changing angle of the sun.

Higher CO_2 uptake rates have been measured in a test room with *Chlorophytum* species (4.4 -5.9 g CO_2 h^{-1}) in a green wall with light intensities of 50 -250 µ mol m^2 s^{-1} and in rooms with very low, stable ACHs it is possible that this could have a small impact on the CO_2 concentration (Torpy, Zavattaro, & Irga, 2017).

4.5 Conclusion

In this chapter the air change rates and reduction in concentration of CO_2, of five offices in two buildings of different types of construction were measured on multiple days with and without plants and over different seasons. The findings showed that the building location, type of construction and design and location of the individual offices had a significant impact on the ACH and the rate of CO_2 reduction within the offices. The introduction of either 12 *Ficus* plants, six *Asplenium* plants or six *Epipremnum* plants did not have a significant impact on the ACHs or rate of CO_2 reduction above that of the normal day to day variation in the offices without plants. Whilst it is possible that a proportion of the reduction in CO_2 concentration was due to CO_2 uptake by the plants, the results of this study were not able to verify the measurements of CO_2 concentration reduction measured in small-scale sealed chambers in Chapter 3.

This chapter has identified the essential necessity of measuring the ACH of individual rooms when researching the impact of plants on IAQ at room scale. Factors which affect the ACH such as weather conditions, building design and occupants must be considered as they can have a greater impact than the plant. Future research should also include measurements of the impact of plants over longer time periods than 1 hour to determine if the CO_2 uptake by the plant is maintained.

Chapter 5

The impact of different environmental conditions on the evapotranspiration rates of indoor plants in experimental chambers

5.1 Introduction

The impact of the air moisture content within a building on the health, comfort, wellbeing and productivity of the occupants is well documented and has been discussed in Chapter 1. The detrimental effects of dry air (low humidity), has been the subject of much debate in the literature (Wolkoff, 2018a; Derby & Pasch, 2017; Bluyssen et al., 1996) but is of particular concern because of the negative association with health symptoms such as dry skin and eyes, and drying of the mucous membranes (Wolkoff, 2018b, 2020; Azuma et al., 2017). The issues of dry indoor air are exacerbated during wintertime, when cold air from outside with a low moisture content is heated and circulated through the building. In combination with heightened susceptibility to other pollutants this is a common cause of occupant discomfort and complaints in office-like environments (Jin et al., 2020; Bluyssen, Aries, & van Dommelen, 2011). Increasing the indoor air humidity can help to alleviate the problems (Wolkoff, 2018a) and whilst this can be achieved through natural or mechanical ventilation, these can introduce other problems and the need for sustainable alternatives has been established (Chenari, Dias Carrilho, & Gameiro Da Silva, 2016; de Kluizenaar et al., 2016; Luengas et al., 2015). High relative humidity (RH) levels, typically above 70%, are also of concern as they can affect occupant's comfort and cause damage to the building fabric (British Standards, 2011; World Health Organization, 2009). Thus, there is a need for sustainable humidification systems which can add moisture to low humidity environments but won't add excessive moisture to humid environments.

Indoor plants potentially offer a sustainable method for the humidification of indoor air, although estimates of their moisture contribution to indoor environments vary from 2.8-400g day^{-1} (Gubb et al., 2018; Zemitis, Borodinecs, & Frolova, 2016; CIBSE, 2012; Tenwolde & Pilon, 2007; Angell & Olson, 1988). Plants can reduce the temperature and increase the moisture content of the air through leaf/canopy transpiration and evaporation from the soil surface, the combined process and total water loss being known as evapotranspiration (ET) (Salisbury & Ross, 1992). Through transpiration, plants draw water from the substrate to the leaves, where it evaporates via stomata and provides cooling for the leaf surface. The process is fuelled by radiant energy from light and the surrounding atmosphere (Gates, 1968). Inherent ET rates vary between plant species (Kemp, Hadley, & Blanusa, 2019; Gubb et al., 2018; Asaumi, Nishina, & Hashimoto, 1995), due to different leaf physiological and morphological traits (Monteiro et al., 2016). The type of photosynthesis also varies between species and is likely to impact the ET rate and the time of day the water vapour is released; most indoor plants utilise C3 form of photosynthesis and open their stomata in the presence of light, but plants which have originated from arid environments have adapted to minimise water loss by using Crassulacean Acid Metabolism (CAM) and open their stomata to fix CO_2 at night when temperatures are cooler and RH is higher (Salisbury & Ross, 1992). Environmental conditions such as substrate physical structure and water-holding capacity, substrate moisture content (SMC), windspeed, light intensity, T_a and RH also have a major influence on the ET rates (Gubb et al., 2018; Zolnier et al., 2000; Baille, Baille, & Laury, 1994; Turner, 1991). Additionally, while the drivers of ET for all species will be similar (e.g. the higher the light intensity, the higher ET, or the drier the soil, the smaller the ET), the rate of species' response to these drivers may vary (Lawson & Vialet-Chabrand, 2019).These factors highlight the importance of species selection for the likely moisture contribution of plants to indoor air.

Two key parameters of indoor environments, T_a and RH, which affect the comfort of building occupants, also have a significant impact on plant ET rates as they determine the vapour pressure deficit (VPD) of the atmosphere. VPD is defined as the difference between the actual vapour pressure of the air (p) and the vapour pressure of the air when it is fully saturated (SVP) at the same temperature (British Standards, 2011). VPD affects stomatal opening in plants, which governs CO_2 uptake and transpiration (Grossiord et al., 2020). Higher T_a and lower RH increase the VPD which increases the ET rate (Grossiord et al., 2020). This suggests that in hot, dry indoor environments plants could make a greater contribution to the air humidity levels, providing water content in the growing substrate is not limiting.

Previous studies have shown that the environmental conditions within indoor environments vary extensively (Bluyssen et al., 1996) and findings from Chapter 4, showed there was a seasonal variation. This identified a need to investigate how the moisture contribution from indoor plants is affected by varying environmental conditions, in particular T_a and RH. It is also important to know if the amount of water emitted from the plants varies during the course of the day as this could influence the indoor humidity levels and comfort and wellbeing of building occupants. Previous studies have not examined the influence of climatic variables on the ET rate of indoor plants whilst keeping other factors constant (species, light intensity, substrate and SMC).

If plants are to be considered as a viable, sustainable method for indoor humidification, it is extremely important to understand the differences in ET rates between species and how these may be impacted by different indoor T_a and RH conditions. The focus of this chapter was therefore to investigate the theoretical moisture contribution plants can make to indoor environments under differing conditions of T_a and RH. The experiments were conducted in controlled environment chambers so that the effect of varying RH and T_a could be investigated whilst other factors affecting ET rate (SMC, light intensity, air flow) were kept constant.

The objectives of this chapter were therefore:

- To determine the ET rate of different indoor plant species under a range of T_a and RH conditions
- To identify the plant with the highest ET rate and greatest potential for impacting the RH within indoor environments
- To determine the diurnal variation in the water vapour emitted from the plants

5.2 Materials and methods

5.2.1 Experimental set up and environmental conditions

A series of successive experiments were carried out in four 'Fitotron HGC' high specification growth chambers (Weiss Technik UK, Loughborough, UK), situated in the UoR, controlled environmental building, between 7th September - 30th October 2020. Five plant species, plus a control of bare substrate, using six replicates per treatment, were tested across each of five different climatic conditions with varying settings of air temperature (T_a) and RH (Table 6.1), to determine how the ET varied under different conditions.

Each chamber had an internal volume 2.43m^3 (dimensions 2.00 x 1.64 x 0.74m). The T_a and RH settings were chosen to represent a range of typical office environmental conditions. The internal T_a and RH were maintained by the cabinets inbuilt system; two EL-USB-2, data loggers (Lascar electronics, Wiltshire UK.) positioned at 60cm below the cabinet ceiling and light source, recorded the actual conditions within each chamber every 10 minutes (Table 6.1). Two plants per chamber were tested at one time as this was found during preparatory tests to be the most efficient use of cabinet space at which the required environmental conditions could be maintained. The air circulation system within the cabinets generated an air flow of less than 0.2 m s^{-1} within each cabinet, measured at the start of the experiments with a Kestrel 4200 Air flow tracker (Nielsen-Kellerman, Boothwyn, USA). Cabinets contained ambient CO_2 concentration (400 ± 150 ppm); this was monitored using a Hobo MX1102 sensor/data logger (Onset Computer Corporation, Bourne, U.S.A.) situated in the centre of the chamber. The experimental settings are shown in Table 5.1.

Office condition	Target setting		Actual		
	RH (%)	**T_a (^oC)**	**RH (%)**	**T_a (^oC)**	**VPD (kPa)**
Cool	50	17	54	17.5	0.92
Warm (Standard)	50	22	55	22	1.19
Hot	50	26	54	26	1.55
Dry	30	22	34	22	1.74
Humid	70	22	72	22	0.74

Table 5.1: Target and actual air temperature (T_a) and humidity (RH) within the controlled environment cabinets. VPD was calculated from the actual RH and Ta measurements using equation 5.1 provided in section 5.2.1.1.

Each experiment was started at 09:00 and ran for 24 hours. A lighting period of 9 hours (09:00 - 18:00) was chosen to replicate a typical working day in an office, during which time normal photosynthesis could be expected to occur. Lighting was provided by Fusion, EDF 39/840 4000k cool white Fluorescent tubes installed within the cabinet ceilings. In preparatory tests, light intensity measurements were taken at multiple positions in each cabinet, using a Testo 545 lux meter (Testo Ltd, Hants, UK) and a SKP 215 PAR Quantum Sensor (Skye Instruments, Powys, UK), following which the lighting was adjusted to provide a light intensity of 1500 lux (20 µmol m^{-2} s^{-1}). This intensity was chosen to provide adequate light for plant activity (i.e. to be above the light compensation point for most indoor plant species), but representative of bright light conditions previously measured in offices environments (Chapter 3).

Figure 5.1: Experimental set up within one of the four Fitotron growth chambers showing the position of the plants and set up of the balance with weight logger attached.

5.2.1.1 Vapour Pressure Deficit

To determine the Vapour Pressure Deficit (VPD), equation 5.1 was used. The actual vapour pressure (p) and SVP of the air was calculated from measurements of the T_a and RH of the air surrounding the plant.

Vapour Pressure Deficit (VPD) ***= Saturation Vapour Pressure (SVP) – Actual Vapour Pressure (p)***

p = SVP x (RH/100) (kPa) 5.1 (British Standards, 2011)

RH = (P/SVP) x 100 5.2

VPD = SVP x (1 - RH/100) (kPa) 5.3

SVP = 0.6105*EXP((17.269*T)/(237.3 + T)) (kPa) 5.4

T = Temperature in ^{0}C

RH = Relative humidity %

5.2.2 Plant material

A selection of five common indoor plant species were chosen to represent a range of different plant physical and physiological characteristics (size, leaf size and shapes, plant metabolism – C3 or CAM) as described in Chapter 2. Six replicates of plant species *Asplenium nidus, Calathea majestica* 'White Star', *Epipremnum aureum, Sansevieria trifasciata laurentii and Ficus benjamina* "Danielle", plus six pots of bare substrate in 3-L containers were tested at each of the environmental conditions. The plants were approximately two years old and acclimatized in an office environment (17 - 22^{0}C, 40- 60 %RH, ~1000 lux) for three months prior to testing.

The plants and bare substrate were watered 1 h prior to the start of each experiment to maintain the substrate moisture content (SMC) at a starting level of 45%. Plant dimensions were measured at the start of the trials and leaf area was measured at the end of the trials (Table 5.2). All measurement and maintenance techniques and substrate are described in Chapter 2.

5.2.3 Measurement of evapotranspiration

The ET rates of plants can be determined in terms of energy usage for changing liquid water into vapour (Pieri I & Fuchs, 1990), predicted through mathematical models (Massmann, Gentine, & Lin, 2019) or determined through measurement (Stokes, 2004).

Methods of measurement include; gravimetric or lysimeter methods (Allen et al., 2011; Salisbury & Ross, 1992), gas exchange and sap flow measurements (Stokes, 2004). The gravimetric method of measuring weight loss was chosen for this study as it been reliably used in previous research (Kemp, Hadley, & Blanuša, 2019; Tan et al., 2015). CBK 32 bench scales (Adam Equipment Ltd., Milton Keynes, UK) were used to measure the weight of each container (substrate plus plant or substrate only) at the start (0 h) and end (23h) of each experiment, allowing one hour changeover between experiments. To approximate the weight loss over a full 24 hours the hourly water loss between 22-23 hours was repeated as the loss between 23-24 hours. The change in weight was assumed to be all due to water loss and was used as a basis to calculate plant ET rate per day. An automatic weight data logger (custom made by Reading University, Chemistry department) attached to one balance within each experimental chamber was used to record the weight of three samples per treatment (plant species + substrate, or substrate only) every 30 minutes.

5.2.4 Data treatment and statistical analysis

Analysis of variance (ANOVA) and post-hoc Tukey HSD tests were used to assess the effect of environmental conditions and plant species on the measured ET rates; repeated measures ANOVA with Bonferroni adjustment was used to compare the effect of environmental conditions within the same species. Variance within the data was checked for normality assumptions and homogeneity. Paired comparison t-tests were used to analyse the differences between light and dark ET rates for individual species in section 5.3.2.

In addition to ANOVA analyses, corelation and regression analysis were conducted to investigate the relationship between VPD and ET rate and to identify which plant parameters had the strongest correlation with ET rate. Regressions were conducted for each set of climate conditions, using ET rate as the dependent variable and leaf area and leaf area density, as the independent variables.

5.3 Results

5.3.1 Plant parameters

Epipremnum had the largest leaf area (5797± 237 cm^2 $plant^{-1}$), followed by *Sansevieria, Ficus, Asplenium* and *Calathea* which has the smallest leaf area per plant (1371 ± 73 cm^2).

Species	**Plant measurements**		
	Height (cm)	**Diameter (cm)**	**Leaf area (cm^2)**
Ficus	55 (± 1)	32 (± 1)	4145 (±193)
Sansevieria	54 (± 1)	29 (± 1)	5440 (±291)
Epipremnum	68 (± 1)	32 (± 1)	5797 (± 237)
Calathea	38 (± 2)	29 (± 1)	1371 (±73)
Asplenium	29 (±1)	40 (± 2)	3568 (±172)

Table 5.2: Mean plant dimensions for each species± SEM. Data are the means of 6 replicates per species, except for Ficus leaf area where data are the means of two replicates.

5.3.2 The effect of plant species and environmental conditions on ET rates

The ET rate of the plants and bare substrate, measured under each of the environmental conditions are presented in Figure 5.2. For simplicity, the term ET rate is used to describe the water loss from all samples although the water loss from the bare substrate is due only to evaporation.

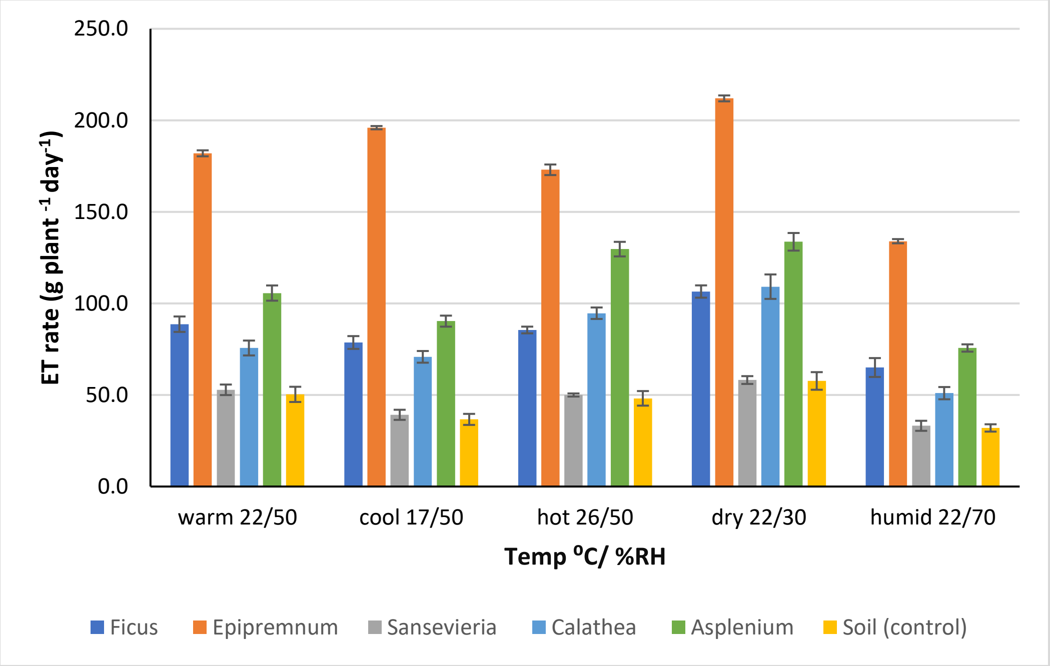


Figure 5.2: A comparison of the ET rates of different plants species under different environmental conditions. ET rates are expressed as grams of water loss per plant per day. Data are the average of six repeats per treatment (N=6) ± SEM.

There was a significant difference in the ET rates of different plant species under all environmental conditions, F (25,150) =3.56, $p<0.001$. All plants, except *Sansevieria,* had a significantly higher water loss than bare substrate under all conditions (all $p<0.05$); there was no significant difference between the ET rate of *Sansevieria* and bare substrate under any conditions. There was a similar trend across all conditions, where *Epipremnum* had significantly the highest ET rate of all plants (all $p<0.001$), followed by *Asplenium, Ficus* and *Calathea*. There were no significant differences between *Ficus* and *Calathea* under any conditions, and *Asplenium* had a higher ET rate than *Ficus* and *Calathea* only under 'hot' and 'dry' conditions ($p<0.05$). The ET rate for *Epipremnum* was typically three to four times higher than for *Sansevieria,* which had the lowest ET rate compared to all other plants (all $p<0.001$). To account for the effect of differences in the size and weight of the plants (Table 5.2) the water loss per plant as a percentage of the total weight (plant + substrate) was compared (data not shown) but the order of species in terms of magnitude of ET rate remained the same, indicating that species was the major factor affecting ET rate differences and not size.

Within the same species, including the bare substrate, there were significant differences in the ET rates between different environmental conditions, F(1.3,45.5)=126.59, $p<0.001$. The highest ET rates were always under 'dry' conditions (30% RH 22°C) and the lowest ET was under 'humid' conditions (70% RH and 22°C). When the temperature was held constant at 22°C and the humidity varied, the ET rate decreased with increasing humidity. *Epipremnum* showed the greatest difference in water loss per day under different conditions, the ET rate was 55% higher under 'dry' conditions (220 g plant^{-1} day^{-1}) compared to 'humid' (142 g) with statistically significant differences between the ET rate at each humidity level (all $p< 0.05$). For all other plants, including bare substrate, significant differences were measured only between 30% and 70%, and 50% and 70% RH, but not between 30% and 50% RH.

When the RH was held constant at 50% and the temperature was varied, the ET rates increased with increasing temperature, but the differences were only statistically significant for *Asplenium* and *Calathea* at 26°C compared to 17°C, and for *Asplenium* at 22°C compared to 17°C (F(1.9,64.9)=31.22, $p<0.001$). The biggest differences were observed For *Asplenium*, where the ET rate at 26°C (130 g plant^{-1} day^{-1}) was approximately 45% greater than at 17°C (90 g plant^{-1} day^{-1}). There was no significant difference between the ET rates at 17°C, 22°C or 26°C for *Ficus, Sansevieria, Epipremnum* or bare substrate.

5.3.3 Relationship between VPD and ET rate

It is well established that Vapour Pressure Deficit (VPD) drives plant transpiration (Grossiord et al., 2020; Massmann, Gentine, & Lin, 2019; Turner, 1991). To investigate further the relationship between the plant ET rates and the changing environmental conditions, the VPD was determined using equations provided in 5.2.4 and the relationship with plant ET rate is presented in Figure 5.3. For all plants and bare substrate, the highest ET rates were at high VPD ('dry' condition).

Figure 5.3 and regression analysis revealed a strong, positive, linear relationship between ET rate and VPD for all plant species, including the bare substrate, which was statistically significant for all plants ($p<0.05$) except for *Epipremnum* ($p=0.24$). The strongest relationship between ET and VPD is for *Asplenium* ($R^2=0.99$, slope = 59.2), and *Calathea* ($R^2=0.962$, slope =52.6). *Epipremnum* had the highest ET rate but the weakest correlation with VPD ($R^2=0.41$,slope= 45.1). The relationship between *Sansevieria* and VPD is comparable with that of bare substrate, showing the plant is having only a marginal effect on the changing ET rate with VPD.

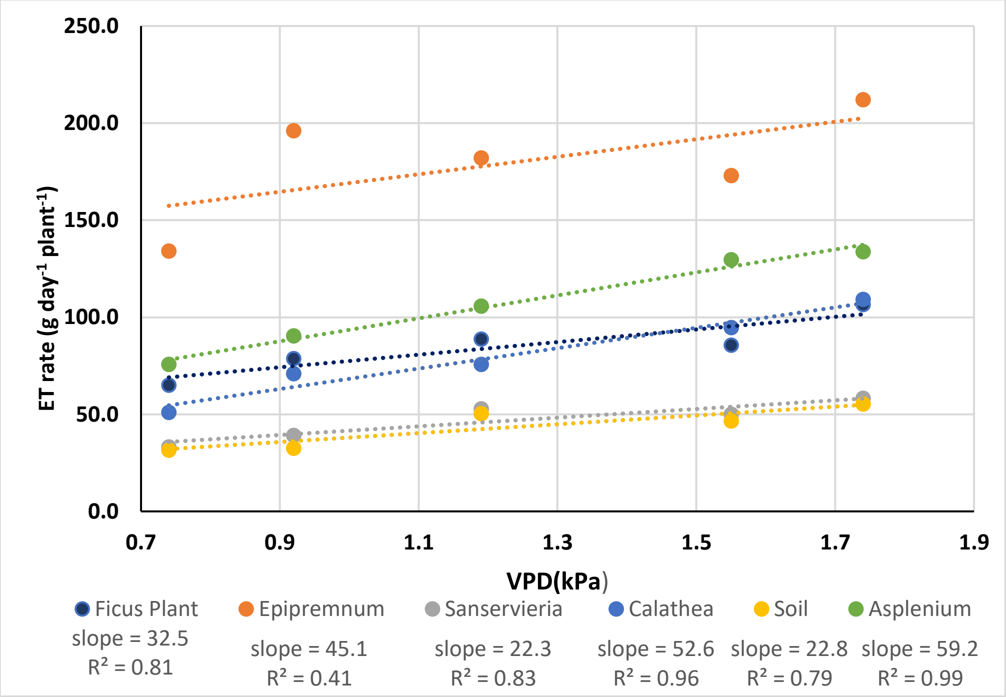


Figure 5.3: Relationship between ET rate and VPD for each plant species. ET rates are based on the mean of six replicates (N=6) per treatment. The regression coefficient (R^2) and slope are provided under each species.

5.3.4 Contribution from transpiration and evaporation

To investigate how much of the water loss was due to plant transpiration and evaporation from the substrate, the approximate contribution of water lost from transpiration was calculated by subtracting the water loss for the bare substrate (evaporation) from the total water loss for each potted plant and expressing this as a percentage (Kemp, Hadley, & Blanuša, 2019; Kerschen et al., 2016) (Table 5.3).

Water lost due to transpiration = (Total water loss from plant + substrate) – Water loss from substrate

	Proportion of ET due to transpiration under different environmental conditions				
	Warm	**Cool**	**Hot**	**Dry**	**Humid**
Epipremnum	72% (±1)	76% (±1)	72% (±1)	73% (±0.5)	76% (±0.4)
Asplenium	52% (±3)	59% (±3)	63% (±2)	57% (±2)	58% (±3)
Ficus	43% (±3)	53% (±2)	44% (±1)	46% (±2)	51% (±5)
Calathea	33% (±3)	48% (±2)	49% (±2)	47% (±4)	37% (±4)
Sansevieria	5% (±4)	6% (±6)	4% (±2)	1% (±4)	4% (±9)

Table 5.3: Contribution of plant transpiration to Total ET. Where ET rate is the total weight loss from one plant over 24 hours. Data are the mean of 6 replicates per treatment (N=6) ± SEM . Where: Water lost due to transpiration = (Total water loss from plant + substrate) – (Water loss from substrate).

The contribution of plant transpiration to total water loss varied with plant species although the order of species, in terms of highest to lowest contribution, remained the same across the majority of the environmental conditions (Table 5.3). *Epipremnum* had the highest contribution from transpiration which ranged from 72- 76% across all conditions, followed by *Asplenium, Ficus* and *Calathea*. The lowest contribution was for *Sansevieria,* where approximately 95% of the water loss was due to evaporation from the soil (Table 5.3 and Figure 5.4).

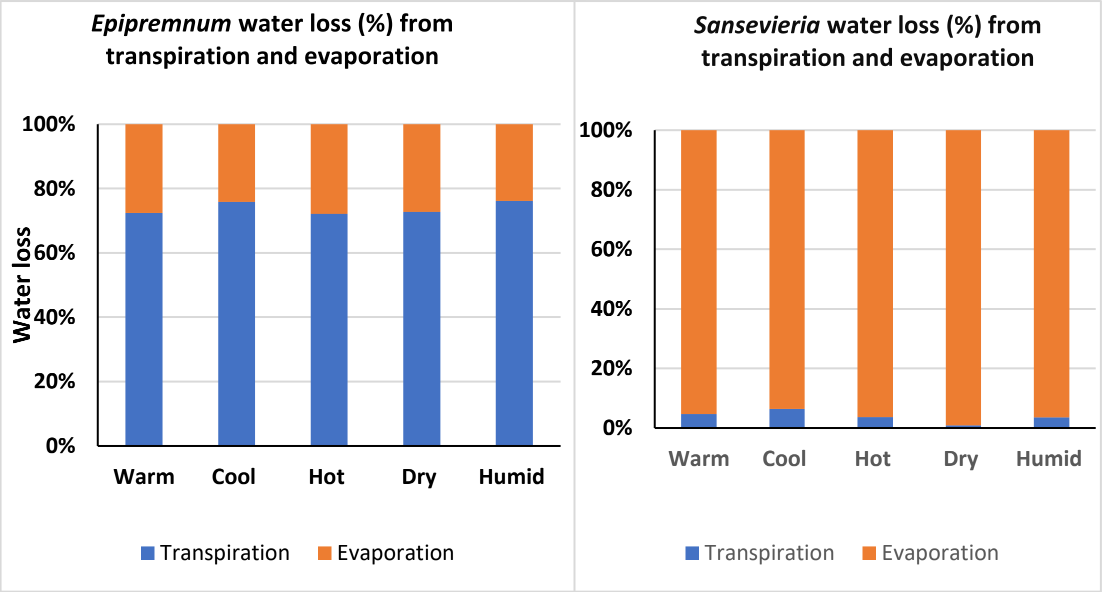


Figure 5.4: A comparison of the two plant species showing the highest and lowest water loss through evaporation and transpiration. Data are the mean of six repeats per treatment.

5.3.5 The effect of leaf area on ET rate under different conditions

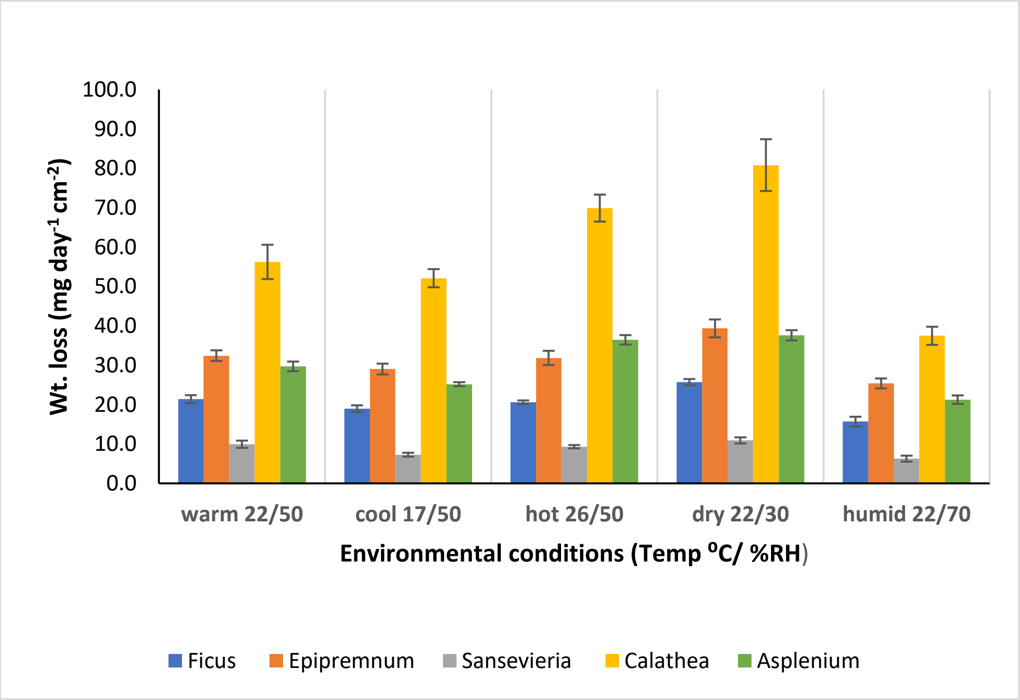


Figure 5.5: Comparison of ET rate per unit leaf area (mg day^{-1} cm^{-2}) of plant species under different environmental conditions. Data are the mean of six replicates per treatment with associated SEM.

Since leaf size, canopy size and density varied between species, to understand if the differences in ET rate between species were due to differences in leaf area, the data was converted to water loss (mg) per unit leaf area (cm$^{2.}$). The results are presented in Figure 5.5

When comparing the ET rate per unit leaf area, *Calathea* which has the smallest leaf area per plant has a significantly higher ET rate per day than all other plants, ranging between 40-80 (mg cm^{-2}), for all conditions (all $p<0.001$), whereas *Epipremnum* which had the largest leaf area*,* ranged between 24.5-38 (mg cm^{-2}). *Sansevieria* had the lowest ET rate (6-11 mg cm^{-2}) across all environmental conditions, which was significantly lower than all plants all ($p<0.05$) except for *Ficus* under warm conditions where the p-value was 0.16. There was no significant difference in the ET rates per unit leaf area, between *Epipremnum, Ficus* or *Asplenium*.

5.3.6 The correlation and regression analysis of LA with ET rate

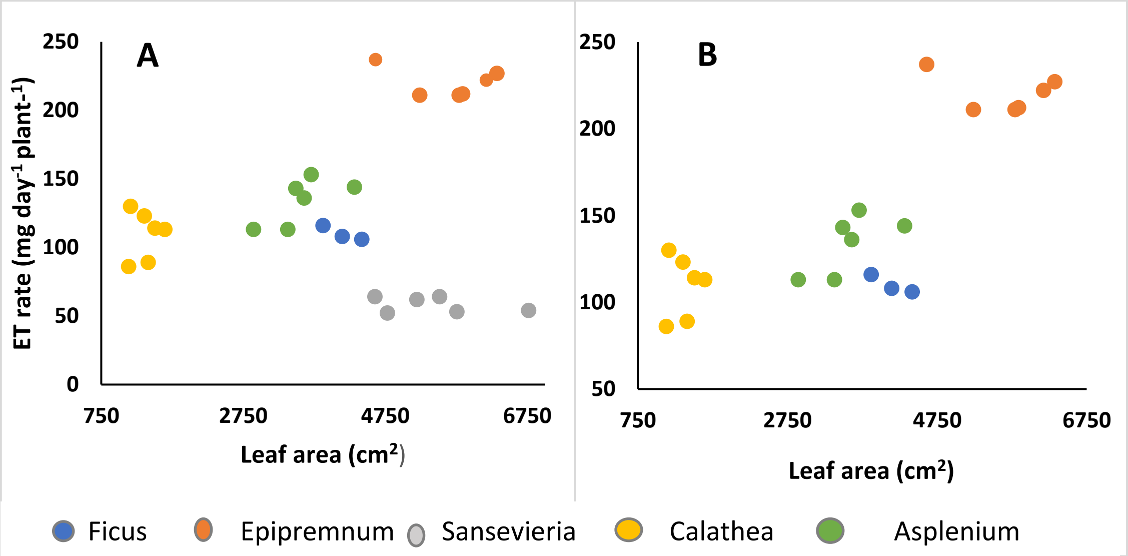


Figure 5.6: Regression models showing the relationship between leaf area and daily ET rate under ‘dry’ conditions for different species. (A) includes all species (N=27) and (B) includes only C3 species (N=21).

The p-values of the Pearson correlation coefficients and regression models, when all plant species (both C3 and CAM plants) were included in the correlation, were 0.23 and 0.055 under dry conditions and humid conditions respectively, showing there was no correlation between leaf area and ET rate(Figure 5.6A).

However, when *Sansevieria*, a CAM plant, was removed from the correlations leaving only C3 plants, the Pearson coefficients were significant, showing positive relationships between LA and ET rate, under dry conditions, r = .80, p(<0.001) and humid conditions, r= .86 (p<0.001), as shown in Figure 5.6B.

5.3.7 Diurnal water loss

To investigate the potential moisture contribution from plants throughout the course of a typical working day and night, the weight loss every 30 minutes over 24 hours were measured, under each set of environmental conditions. Although the mass of water loss varied with environmental conditions, the distribution of water loss over 24 hours followed a similar pattern under all conditions for each species. The results under 'dry' conditions are presented in Figure 5.7 to illustrate the pattern of water loss over a 24-hour period.

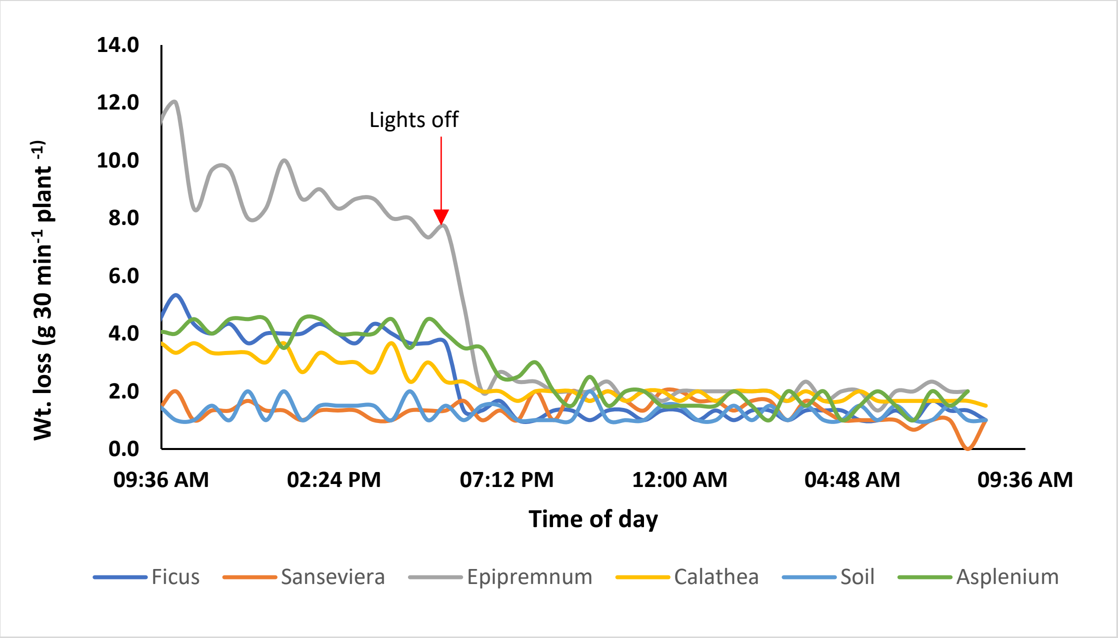


Figure 5.7: Diurnal water loss for all species under 'dry' conditions (22°C and 30% RH). Data are the mean of 3 replicates per treatment. The approximate time when the lights were turned off is shown with the arrow.

After a short settling down period following the start of the experiments, for *Ficus, Epipremnum, Calathea* and *Asplenium* the greatest water loss coincided with the lighting period, between 09:00 – 18:00 when ET rates were between 30-80% higher than during the dark period. In Figure 5.7, the arrow indicates the time when the lights are turned off shortly after 18:00, and this can be seen to be followed by a sharp fall in the ET rate for all species except *Sansevieria*. The ET rates and the differences in water losses between light and dark for *Sansevieria* are considerably smaller than all other plants and follow a similar pattern to bare substrate. Under 'dry' and 'cool' conditions the water losses for *Sansevieria* were higher during the dark compared to the light period.

The variation in ET rates during light and dark periods were determined for each species and the results are presented in Table 5.4.

		ET rate g hr^{-1} plant^{-1}				
		Dry	**Hot**	**Cool**	**Warm**	**Humid**
Ficus	Light	7.6 (± 0.4)	5.5 (± 0.3)	5.0 (± 0.6)	5.8 (± 0.3)	4.2 (± 0.6)
	Dark	2.5 (± 0.1)	2.3 (± 0.2)	1.5 (± 0.2)	2.0 (± 0.1)	1.3 (± 0.2)
Sansevieria	Light	2.6 (± 0.1)	2.8 (± 0.1)	1.6 (± 0.1)	2.7 (± 0.2)	1.6 (± 0.2)
	Dark	2.8 (± 0.0)	2.0 (± 0.5)	1.8 (± 0.0)	2.3 (± 0.1)	1.3 (± 0.2)
Epipremnum	Light	16.7 (± 0.7)	12.8 (± 1.5)	10.7 (± 2.6)	13.1 (± 0.6)	12.3 (± 0.5)
	Dark	3.9 (± 0.1)	4.0 (± 0.1)	2.1 (± 0.5)	4.0 (± 0.2)	2.5 (± 0.1)
Calathea	Light	6.1 (± 0.6)	5.5 (± 0.4)	4.6 (± 0.4)	3.9 (± 0.1)	2.7 (± 0.4)
	Dark	3.8 (± 0.3)	2.8 (± 0.2)	2.2 (± 0.2)	2.1 (± 0.1)	1.7 (± 0.2)
Asplenium	Light	8.3 (± 0.1)	8.6 (± 0.3)	5.5 (± 0.9)	6.5 (± 0.2)	5.3 (± 0.2)
	Dark	3.4 (± 0.1)	3.6 (± 0.1)	3.1 (± 0.2)	3.2 (± 0.1)	2.6 (± 0.2)
Control	Light	2.8 (± 0.0)	2.8 (± 0.1)	1.6 (± 0.1)	2.4 (± 0.0)	1.4 (± 0.0)
	Dark	2.4 (± 0.1)	1.8 (± 0.0)	0.5 (± 0.0)	1.9 (± 0.0)	1.3 (± 0.0)

Table 5.4: ET rates for each species during light and dark periods under different environmental conditions. ET rates are the mean of the weight loss measured every 30mins and averaged over an 8-hour period. Data are the mean of three replicates per treatment (N=3) ± SEM.

All plants had significantly higher ET rates during light periods under 'hot' conditions ($p<0.05$) and *Epipremnum,* the plant with the highest ET rate, showed the biggest response to the changes between light and dark. The differences in ET rate between light and dark were significant for *Ficus* and *Asplenium* under all conditions, and for *Epipremnum* and *Calathea* under all conditions except ‘cool’ and ‘humid respectively ($p<0.05$). All plants except *Sansevieria,* had higher ET rates than bare substrate (Control) during the lighting period. For *Sansevieria* most of the water loss is due to evaporation, but during the dark period, the water losses are actually higher compared to the bare substrate across all environmental conditions indicating plant transpiration is occurring.

5.4 Discussion

This chapter investigated the effect of changing the environmental conditions of temperature and RH on the ET rates of five different plant species to assess their potential humidification capacity within indoor environments.

5.4.1 The effect of plant species on ET rates

The ET rate of plants determines the amount of moisture they contribute to the surrounding atmosphere. The difference between species is therefore important when selecting plants as potential humidifiers for indoor environments. There was a significant difference in the daily ET rates between plant species ranging from 33 to 220 g per plant, across all species and conditions. *Epipremnum* had the highest ET rate of all plants tested, under all conditions and is therefore the best performing species in terms of humidification capacity per plant for dry indoor environments. Higher transpiration rates were also observed for *Epipremnum aureum* compared to *Ficus benjamina* in a study in glasshouses made over 10 hours at a range of temperatures, although light intensity and RH levels were not reported (Asaumi, Nishina, & Hashimoto, 1995).

However, in these experiments, *Epipremnum* also had the largest leaf area of C3 plants and regression analysis showed there was a significant positive relationship between leaf area and ET rate for all C3 plants, which is expected as water vapour is emitted through the stomata located in the leaves. On a leaf area basis, *Calathea* had the highest ET rate. When considering the humidification potential of different species for indoor environments, the size and volume of the plant also need to be considered, and although *Calathea* could make a greater water vapour contribution per unit leaf area, it also had a lower leaf area density compared to other plants and therefore a greater quantity of plants would be required to equal the leaf area of other species. *Calathea* is a broadleaf plant, originating from tropical rainforests where are they are found growing in the understory of the forest canopy. In these humid environments water conservation is less critical than plants growing in more arid environments, but it’s broad leaves would help it to capture more light from the shady conditions of its natural habitat.

Sansevieria had the lowest ET rate of all plants tested and was not significantly different to the water loss from the bare substrate. It also had the lowest ET rate when compared on a unit leaf area basis indicating it would contribute the least amount of moisture to an indoor environment. *Sansevieria* originates from hot arid climates, it is adapted to conserve water by utilising CAM photosynthesis and the ability to store water in its thick succulent leaves (Virzo De Santo, Fioretto, & Alfani, 1981). These traits make it very efficient for water utilisation and a good choice of plant for indoor environments where low maintenance or low moisture contribution are required, but it would not be very useful for humidification in a dry indoor environment.

It is difficult to make detailed comparisons with data from previous studies as different plant species and conditions of temperature, humidity and light intensity were used which were typically not controlled during the experiments. However, the ET rates measured in this study are in the same order of magnitude as those reported for other indoor plants (Gubb et al., 2018; Kerschen et al., 2016; Asaumi, Nishina, & Hashimoto, 1995). In experiments to determine their formaldehyde removal capability, the ET rates of eight indoor plants were estimated from the changes in humidity levels within a sealed chamber, at very low light intensity (330 lux, 4.8 µmol m^{-2} s^{-1}), (Panyametheekul et al., 2019); *Epipremnum* was reported to have one of the highest ET rates (2.7 g h^{-1}) which is comparable with the ET rate measured for the non-lighting period under humid conditions in this experiment (2.5g h^{-1}) and their estimate for *Sansevieria* (1.7 g h^{-1}) was comparable with the ET rate measured under humid conditions here (1.6 g h^{-1}). In the study by Panyametheekul et al. (2019), the number of stomata was shown to have a positive linear correlation with ET rate and *Epipremnum* had one of the highest number of stomata per plant, compared to the eight plants tested. Although the number of stomata weren't measured in this research, the high number of stomata associated with *Epipremnum* in the study by Panyametheekul et al. (2019) could partially explain its high ET rate. *Hedera helix* and *Spathiphyllum wallisii* had the highest ET rates (~ 70 g $plant^{-1}$ day^{-1}) in a group of seven species measured under low light (10 µmol m^{-2} s^{-1}) in an open office environment where temperature, RH and air flow were not controlled (Gubb et al., 2018). In experiments measuring the effect of cold stress on indoor plants, *Sansevieria* was found to have the lowest transpiration rate and highest water use efficiency (Gupta et al., 2016). The C3 plant, *Chlorophytum comosum,* was shown to have a higher ET rate than the CAM plant, *Crassula argentea,* at both high and low humidity in controlled chamber studies (Kerschen et al., 2016).

The ET rates measured in this study showed that all plants except *Sansevieria* would contribute more moisture to indoor air than evaporation of water from bare substrate alone, due to the additional contribution of plant transpiration. *Epipremnum* had the highest contribution from transpiration to total water loss compared to all other plants. The transpiration contribution remained stable between 72-76% across all environmental conditions, showing that evaporation from the substrate and transpiration activity in the plant both respond to changes in environmental conditions.

Of the C3 plants tested here, *Calathea* had the lowest contribution from transpiration ranging from 33-49% across all conditions, showing that evaporation from the soil makes a significant contribution to the water lost by this species. This is partially explained by the lower leaf area and leaf density in *Calathea* compared to other plants. For *Sansevieria,* the water loss measured over 24 hours was virtually all due to evaporation and this species would therefore offer little advantage over bare substrate for humidification within indoor environments. These results show that plant species have inherent physiological differences which affect the ET rates and water use of plants. This supports the findings from previous studies which also showed differences between plant ET rates, extended down to a cultivar level (Gubb et al., 2018; Monteiro et al., 2016).

These results highlight the importance of species selection with regard to the humidification potential of different plants, whereby plants such as *Epipremnum* with a high transpiration rate can make a greater contribution to indoor humidity.

5.4.2 The effect of varying temperature and RH on ET rates

Changes in T_a and RH had a significant impact on the ET rates for all plants and bare substrate tested, but the size of the effect was species-dependant. All plants showed the greatest water loss under ‘dry’ (low humidity) conditions and ET rates decreased with increasing RH and with decreasing air temperature. The strong, positive linear relationship with VPD under the test conditions indicates that the plants are reacting to pressure changes in the surrounding atmosphere and that transpiration is increasing with increasing VPD. This increase in transpiration would be expected to continue to a maximum after which the high VPD will become limiting and the transpiration rate will plateau and then decrease (Grossiord et al., 2020; Merilo et al., 2018). Air temperature and RH are known to affect water loss from plants (Salisbury & Ross, 1992), but In the range of conditions tested in this study, changes in humidity between 30-70% RH, had a greater impact on the ET rate compared to changes in temperature between 17-26^{o}C. The response to the changing environmental conditions varied with species; *Epipremnum*, with the highest ET rate, showed the biggest difference in water loss across environmental conditions which ranged between 142g plant^{-1} day^{-1} under ‘humid’ conditions up to 220 g under ‘dry’ conditions, whereas for *Sansevieria*, the water loss ranged from 33–58 g plant^{-1} day-^{1}. *Asplenium* and *Calathea* showed the strongest correlation and rate of change between ET rates and VPD, indicating that the rate of moisture loss from these species in indoor environments would be more strongly affected by changes in the environmental conditions. Variability in response to VPD between different species (Grossiord et al., 2020) and greater variation in the ET rates of broadleaf species with changing environmental conditions, has also been shown in in previous studies (Kemp, Hadley, & Blanusa, 2019). In this study only well-watered conditions were used, but other researchers have shown that the ET rate decreases reduce as the substrate dries out but the response also varies with species (Grossiord et al., 2020).

5.4.3 The diurnal water loss

The diurnal water loss showed the ET rates were consistently higher under light compared to dark conditions for all C3 plants, across all environmental conditions. They were also higher compared to the bare substrate during the light but there was no significant difference during the dark period, indicating that the higher water losses are due to plant transpiration. *Epipremnum* showed the biggest increase in water loss under light conditions of all the plants tested, which was between three to five times greater during the light period compared to the dark across all conditions. *Ficus* showed the next highest response to light, with ET rates approximately two to three and a half times greater under light compared to dark conditions, this was followed by *Asplenium* and *Calathea. Sansevieria* did not follow the same response to light and dark as other species. It had higher water losses during the dark period than the bare substrate control across all environmental indicating that the plant was transpiring during the dark, probably as a result of its CAM photosynthesis.

The results from the diurnal water loss experiments indicate that for C3 plants, the highest moisture contribution within indoor environments, could be expected to occur when there is sufficient light for photosynthesis, during a normal working day. For CAM plants such as *Sansevieria*, the moisture contribution could be expected to be higher under dry conditions at night compared to during the daytime.

5.5 Conclusion

The results from these experiments show that there is a significant difference in the humidification capacity between different indoor plant species. *Epipremnum* had the highest ET rate under all conditions out of all the plants tested and would have the greatest humidification potential for indoor environments. *Sansevieria* had the lowest ET rate, which was not significantly higher than bare substrate and it would have very little impact on the humidity levels of indoor environments, this species would therefore be a good choice for environments where a low moisture contribution is required. These results highlight the importance of species selection when choosing plants for humidification purposes.

Changes in the environmental conditions of temperature and humidity, had a significant impact on the ET rate of the plants. ET rates were highest at low humidity levels and high temperatures; thus, the greatest water vapour contribution would be made to hot, dry indoor environments. The ET rate decreased with increasing RH and the moisture contribution from plants would therefore be expected to be lower in cool rooms with high humidity levels.

The clear difference in response by plants species to changing environments shows the importance of species selection for different environments. These results suggest that plants with high ET rates and low LCPs, have the potential to increase the water vapour concentration in low humidity environments and therefore benefit the comfort of the occupants.

In office environments the main moisture contribution is from human respiration and perspiration and typical contribution rates vary between 30 -90 g hr^{-1} $person^{-1}$, depending on the person, activity level and environmental conditions (CIBSE, 2006a). Based on the findings from this study, the moisture contribution from one potted *Epipremnum* plant (1.6 -16.7 g $plant^{-1}$ $hour^{-1}$) would therefore be small in comparison to other sources but could be significant if a higher number of plants were used. To equal the amount of moisture emitted by one person, depending on the room conditions an estimated five to nineteen *Epipremnum* plants would be required and over twice this number of plants if using other species.

The theoretical prediction and experimental validation of moisture contribution from plants within a real office environment are investigated in Chapter 6.

Chapter 6

The impact of indoor plants on the moisture content of the indoor air within small office environments

6.1 Introduction

The importance of the moisture content of indoor air due to its impact on the health, comfort and productivity of the building occupants has been established in Chapters 1 and 5. Within office environments, both low and high humidity levels are of concern, low relative humidity (RH) has been associated with increased symptoms associated with drying of mucous membranes such as irritation of the eyes and upper airways (Wolkoff & Kjærgaard, 2007), reduced performance in office tasks (Wyon et al., 2006), higher absenteeism (Arundel et al., 1986) and possibly reduced work performance (Wolkoff, 2018a). The risk of infection for building occupants can increase at low humidity as the survival and airborne transmission of bacteria and viruses has been shown to increase at low RH (Moriyama, Hugentobler, & Iwasaki, 2020; Lowen et al., 2007). The environmental conditions of the workplace can also impact workers stress levels which is a major cause of working days lost in the UK (Health and Safety Executive, 2020). A study in the USA of 134 office workers, showed a 25% lower stress response, and better sleep quality when participants spent the majority of their time in 30-60% RH compared to drier environments (Razjouyan et al., 2020). Increasing the humidity can help alleviate these problems.

Ambient T_a and RH have been shown to have a significant impact on the perception of IAQ and thermal comfort of building occupants; typically perceived air quality decreases with increasing T_a and RH (Yao, Li, & Liu, 2009; De Dear, 2004; Fang, 1998; Toftum, Jørgensen, & Fanger, 1998; Berglund & Cain, 1989). There is no single 'correct value for thermal comfort as individual preferences vary, but the recommended values of T_a and RH within thermal comfort standards are important as they determine the energy consumption by a building's environmental systems (Yao, Li, & Liu, 2009). For office work in the UK, the Health and Safety Executive have set a legal minimum T_a of 16 °C (Health and Safety Executive, 1992) but there is no specific legal standard for humidity levels and recommendations vary; British Standards (2011) recommends that levels of RH are maintained between 45-60% RH at 18°C to 24°C, whilst CIBSE (2006b) advises that humidity in the range of 40%-70% is generally acceptable. Excessively high humidity (above 70% for several days) is a serious concern due to the risk of condensation and mould growth, leading to a health risk for occupants and possible damage to the material condition of the building (Brambilla &

Sangiorgio, 2020; Dedesko & Siegel, 2015; British Standards, 2011; World Health Organization, 2009).

Maintaining the indoor RH within acceptable levels through mechanical systems is energy intensive and expensive and there is a need for sustainable humidification systems (the term 'humidification' refers to the addition of water vapour). The findings from Chapter 5 and previous research conducted in controlled environmental chambers (Panyametheekul et al., 2019; Ryu et al., 2019; Kerschen et al., 2016) have shown that through the process of evapotranspiration (ET), indoor plants potentially offer a sustainable method for the humidification or dry indoor air but the amount of water vapour emitted varied with species and is dependent on the T_a and RH of the air within the chambers. In real world environments there are many additional variables which can influence the RH of the indoor air such as the occupants and their behaviour, the building design, the air change rate and seasonal variation in outdoor weather conditions (Tang et al., 2020; Zemitis, Borodinecs, & Frolova, 2016; Nguyen, Schwartz, & Dockery, 2014). These need to be understood to accurately assess the humidification potential of indoor plants. Very few studies have investigated the impact of indoor plants on the humidity in real office environments and findings from those which have varied from no impact on RH, to ten percent increase in RH over 24 hours (Tudiwer & Korjenic, 2017; Su & Lin, 2015; Mangone, Kurvers, & Luscuere, 2014; Smith & Pitt, 2011; Wood et al., 2006). None of these studies have measured the water vapour contribution from the plant and its actual impact on indoor humidity whilst considering the ACH of the room or the outdoor climate and any seasonal variation. Additionally, most studies have measured RH, which is dependent on $T_{a,}$ and they have not accounted for the impact of temperature changes on the RH.

Given the importance of maintaining the indoor T_a and RH within recommended levels, it is essential for building designers, managers and occupants that the impact of indoor plants on the water vapour concentration within real office environments is better understood if they are to be considered as sustainable, alternative humidification systems.

The objectives of this chapter were therefore:

- To determine how indoor plants affect the absolute humidity and air temperature within real indoor office environments during the working day and to determine the extent, if any, of seasonal variations.
- To measure the ET rate of plants in an office environment over different seasons and to determine if measurements made in small scale environmental chambers are verified at room scale.

6.2 Materials and Methods

A series of experiments were conducted in three cellular offices situated within Building 2, a naturally ventilated building within the UoR between December 2018 - February 2021. To eliminate the effect of occupants on the AH and the ACH of the rooms, all experiments were conducted when the offices were unoccupied. During 2019 this was typically over weekends and holidays when the central heating was set to the out of hours regime described below in 6.2.2. During winter 2021, due to national lockdown restrictions in the UK, it was possible to conduct a limited number of experiments during weekdays when the building was unoccupied, and the heating control was then set to working day regime.

6.2.1 The experimental test offices and buildings

The three cellular offices 1, 2 and 3, located in Building 2 (Chancellors Building), a two-storey, prefabricated, modular building constructed in 2015, are described in detail in Chapter 4 (4.2.1.2). To reduce the variability associated with the ACH, experiments were conducted with the natural ventilation (doors, windows and trickle vents) closed. The offices were considered appropriate for use in these experiments as the findings from Chapter 4 showed that they had low ACH rates with the natural ventilation closed, which should enable potentially small changes in moisture content due to the presence of plants to be detected. The experiments are summarised in table 6.1.

Season and year	**Offices used (Volume)**	**Conditions tested**
Winter 2019 (December 2018 – January 2019)	1 (28.3 m^3) 2 (30.4 m^3)	With and without 12 *Ficus* or 6 *Asplenium* plants in each office Out of hours heating regime
Spring 2019 (April 2019)	1 (28.3 m^3)	With and without 12 *Ficus* plants Out of hours heating regime
Summer 2019 (August -September 2019)	1 (28.3 m^3)	With and without 12 *Ficus* plants No heating
Winter 2021 (January-February 2021)	1 (28.3 m^3) 3 (30.6 m^3)	With and without 6 *Epipremnum* plants in office 1, no plants in office 3 Working day heating regime

Table 6.1: Summary of the office humidity experiments conducted, and the offices used

The heating within the building is delivered from electric wall panel heaters and is controlled by a central Building Management System linked to several thermostats positioned throughout the building. The heating system is enabled to maintain the T_a above 19°C during normal occupancy times (08:00-18:00 Monday to Friday), which is described here as *working day* heating regime, and above 12°C outside of these hours; overnight, weekends and closure periods and this is described as *out of hours* regime.

6.2.2 Environmental parameters

6.2.2.1 Definitions

Relative humidity (RH) is defined as the amount of water vapour contained within a given volume of air compared with the maximum amount the air could hold at a given temperature. It provides a measure of the relative concentration of moisture in the air and is expressed as a percentage (British Standards, 2011; Awbi, 2003). The T_a determines the amount of water vapour the air can hold, therefore RH is dependent on both water vapour concentration and T_a; RH is inversely correlated with T_a (British Standards, 2011; Awbi, 2003).

Absolute humidity (AH) represents the mass of water vapour in a given volume of air and in this thesis is expressed as grams per cubic metre of air (British Standards, 2011). This provides a measure of the true water vapour concentration of the air independent of T_a. AH is therefore used in this study to measure the impact of plants on the indoor water vapour concentration. RH is useful when considering people's thermal comfort and is used in building design standards.

6.2.2.2 Measurement of environmental parameters

Full details of the sensors used, and their accuracy are provided in Chapter 2.

Three calibrated, Hobo MX1102 data loggers were used to record the T_a (°C) and RH (%) at 5-minute intervals, within each office. The measurements were taken at the same time as the CO_2 concentration measurements outlined in Chapter 4 and the sensor locations are provided in Figure 4.11 (section 4.2.3). Measurements of the T_a and RH within the rooms before and after the addition of the CO_2 gas showed there was no measurable impact of gas introduction on either parameter (Data not shown). The outdoor measurements for T_a, RH and air pressure for the same time periods were taken from the UoR, Meteorological office observation site, approximately 1.1

km east of the offices. The outdoor weather conditions were monitored, and experiments were conducted to avoid days of strong winds and heavy rain.

Lighting was provided by electric ceiling and desk lights; daylight entered the room through one external window in each room (104cm x 96 cm) to maintain a light intensity of 1000 lux as described in Chapter 3. The electric lights were on between 09:30 and 17:30 approximately. The air pressure within all offices, measured at the start of each experiment ranged between 985-1019 hPa and the indoor air velocity was below 0.02 m s^{-1}.

6.2.3 Plant material

The twelve *Ficus benjamina,* six *Asplenium nidus* and six *Epipremnum aureum* plants were used for the experiments; their preparation and maintenance are described in detail in Chapter 2. *Ficus* and *Asplenium* species were selected for the 2019 experiments as these demonstrated the highest CO_2 uptake capability during chamber experiments in Chapter 3. This was taken as an indicator that these species would have highest ET rates, as leaf-level water loss takes place through the same stomatal openings as CO_2 uptake (Salisbury & Ross, 1992). Further findings from chapter 5 revealed that *Epipremnum* plants had the highest ET rate out of the range of plants tested, and this species was therefore selected for use in the winter 2021 experiments as it could be expected to have the greatest impact on the indoor humidity within an office.

To determine the ET rate within each office, each plant was weighed in its container, including substrate, at the start (0 h) and end (23 h) of each experiment to allow for preparation time each day. To approximate the weight loss over a full 24 hours the 23 hourly water loss was divided by 23 and multiplied by 24. The change in weight was assumed to be all due to water loss and was used as a basis to calculate plant ET rate per day. The substrate surface was left uncovered during the experiments. For the purposes of the determination of the impact of the plant on the AH within the offices, it was assumed that all the water lost was emitted into the office as water vapour and contributed to the moisture content of the indoor air.

The health of the plants was checked visually at the start and end of each set of seasonal experiments and all plants remained healthy throughout the studies.

6.2.4 Data and statistical analysis

Data from the three sensors in each office were used to determine the five-minute mean T_a/RH for each office for each experiment.

6.2.4.1 Calculation of absolute humidity

To provide a measure of the mass of moisture in the air and take account of the effect of variation in T_a, the measurements of T_a (°C) and RH (%) were used in equation 6.1 to calculate the absolute humidity (AH) of the indoor and outdoor air for each experiment.

$$\mathbf{AH = (2170*p)/\ (T_a + 273.3)} \qquad (6.1) \quad \text{(British Standards, 2011)}$$

AH = Absolute humidity (moisture content) of air (g m^{-3})
p = (Actual vapour pressure in kPa) = SVP x (RH/100)
RH = (P/SVP) x100
SVP = (saturation vapour pressure in kPa) = 0.6105*EXP((17.269*T)/(237.3 + T))
T_a= Dry bulb Temperature in ^{0}C

6.2.4.2 Comparison of the changes in T_a and AH

The starting time for the data analysis of the indoor and outdoor T_a and RH was taken as 10.00 am when the sensor readings had stabilised after the experiments had been set up. Data were analysed for the time periods of 1 h, 3.5 h and 7.5 h after the start. These time periods were chosen to provide a 1-hour comparison with the chamber studies and to represent the working periods until lunchtime (13:30) and the end of a typical working day in the office (17:30). The mean of the 15-minute readings around each time was taken as the data point to be used for each time period (e.g. the mean of the readings at 09:55, 10:00 and 10:05 were taken as the starting value at time 0 h). To examine how the presence of plants influenced the change in moisture content over the course of the working day and to take account of variation in the AH concentration across the different test days, the change in AH and T_a were determined by subtracting the starting values (time 0 h) from the measurements after 1 h, 3.5 h and 7.5 h.

Repeated Measures ANOVA with post-hoc Tukey's honest significance difference test (Tukey HSD) was used to assess the effect of plant species on the change in AH and T_a within each office during Winter 2019. Variance within the data was checked for normality assumptions and homogeneity. When there were only two groups for comparison (Plants or No plants) paired comparison t-tests were used in Spring 2019, Summer 2019 and Winter 2021. To compare differences between seasons, Repeated Measures ANOVA and Post-hoc Scheffé multiple comparison tests were used as the group sizes were uneven. Differences are reported as statistically significant where $p \leq 0.05$.

6.2.4.3 Calculation of the moisture generation and moisture excess using moisture balance model

Moisture balance models are based on the conservation of mass of water vapour and are widely used to estimate the indoor humidity levels and moisture generation within buildings (Teleszewski & Gładyszewska-Fiedoruk, 2020; British Standards, 2012; Glass & Tenwolde, 2009; Awbi, 2003). The change in moisture content within a room over time depends on the amount of moisture entering and leaving the room plus the amount generated within the room, plus the moisture lost or gained by adsorption/desorption from the building and interior materials. The model takes into account the air exchange within the room and the differences in indoor and outdoor AH concentrations over a given time. They are therefore a useful method of comparing the changes in moisture content within the offices on different test days and calculating the theoretical moisture generation from the plants.

The rate of change in the moisture concentration within a room, under non-steady state conditions can be expressed by the moisture balance equation 6.2.

$$\mathbf{V\ dci/dt = G - Q(M_i - M_o) - M_{sorb}} \qquad (6.2)\ \text{(Glass \& Tenwolde, 2009)}$$

Assuming steady conditions:

$G = Q\,(Mi - Mo) + M\ sorb$

Where:

G = moisture generated in room (g h^{-1})

V = Volume room (m^3)

Q = Air flow rate ($m^3\ h^{-1}$) (where Q = ACH x Volume room)

M_o = outdoor moisture concentration (AH) (g m^{-3})

M_i = indoor moisture concentration (AH) (g m^{-3})

M_{sorb} = moisture added or removed by absorption/desorption (g h^{-1})

t = time (h)

The left side of equation 6.2 gives the mass rate of change of water vapor in the room, and the right side includes the main factors which affect this; the apparent moisture production rate within the room, the rate of water vapour removed by air exchange, and the moisture sorption rate. Under steady conditions, where the indoor water vapor concentration is relatively constant, the left side goes to zero.

Q was calculated using the ACHs determined in chapter 4 and the volume of each office. The materials within each room remained the same for each experiment and assuming steady state conditions the contribution from sorption was neglected, as proposed by Loudon (1971). As there were no occupants or other sources of moisture production in the offices, it is assumed that G = moisture production from the plants. The difference between the moisture content on the test days with and without plants in the office should be due to the moisture contribution from the plants.

6.3 Results

Initially, the 5-minute data means for the indoor and outdoor T_a, RH and AH, were plotted individually for each day and office to provide detailed response patterns which generated an extensive number of plots. The results are presented in summary form below as means (±SEM) for the repeated test days for each season and condition investigated (Plants or No plants). T_a changes in relation to the impact on CO_2 concentrations are also discussed in Chapter 4.

6.3.1 Winter 2019

During winter 2019, the mean daytime indoor AH within Office 1 and 2 across all test days ranged between 8.9-10.4 g m^{-3} and was significantly higher (typically 40-50%) than outdoors where the outdoor AH ranged between 4.7-7.7 g m^{-3} (Figures 6.3 A and B).

For both offices the mean indoor AH was lower on the test days with plants in the office, compared to the days without plants, in particular the days with *Asplenium* plants in Office 1 and *Ficus* plants in office 2 were significantly lower (between 7-17%), than the days without plants. From the different starting concentrations, the indoor AH gradually settled during the morning, and then after falling or rising through the morning, it increased to a peak concentration during the afternoon between 15:00-18:00. The outdoor AH also increased during the morning but reached its peak concentration earlier, between 12:30-14:00.

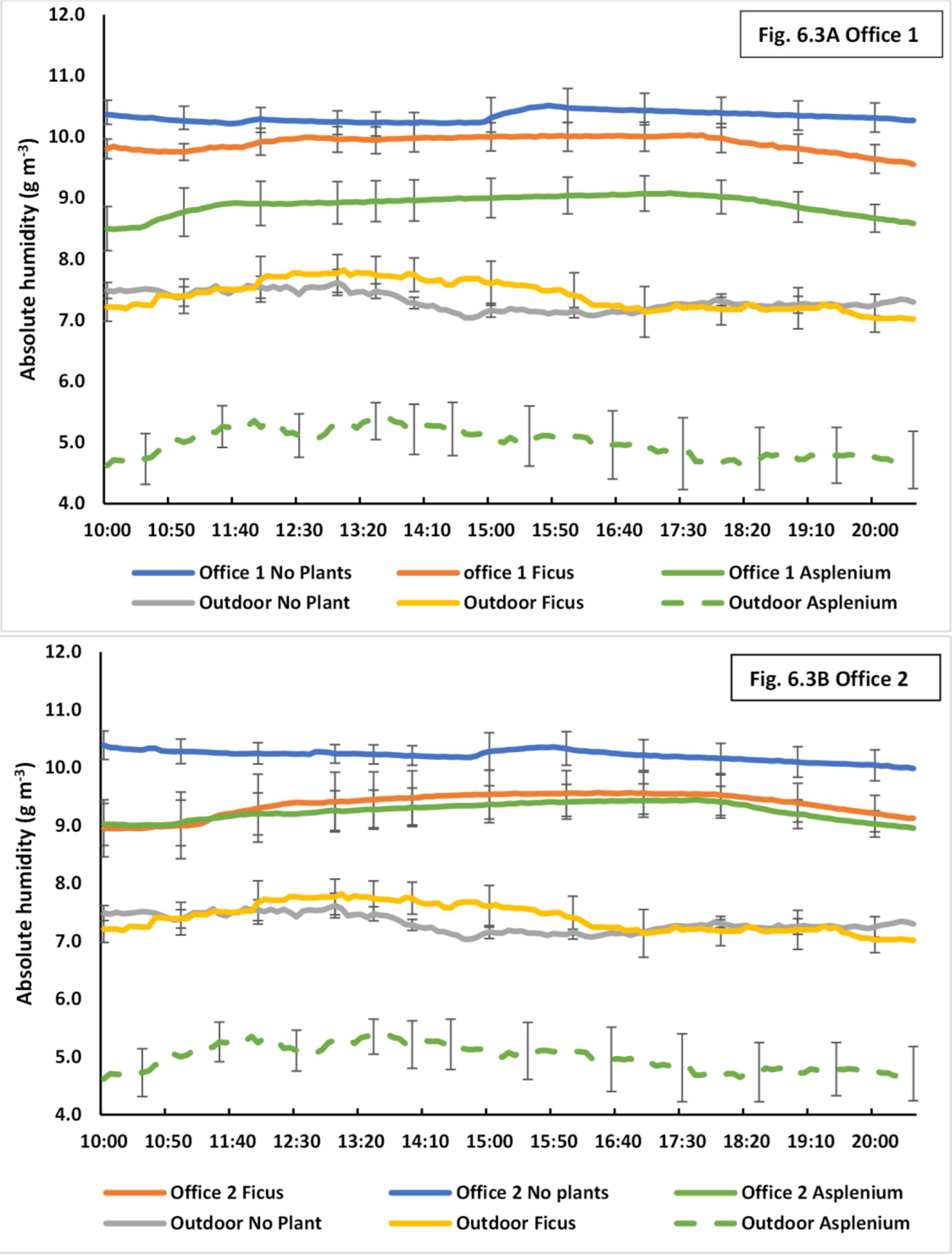
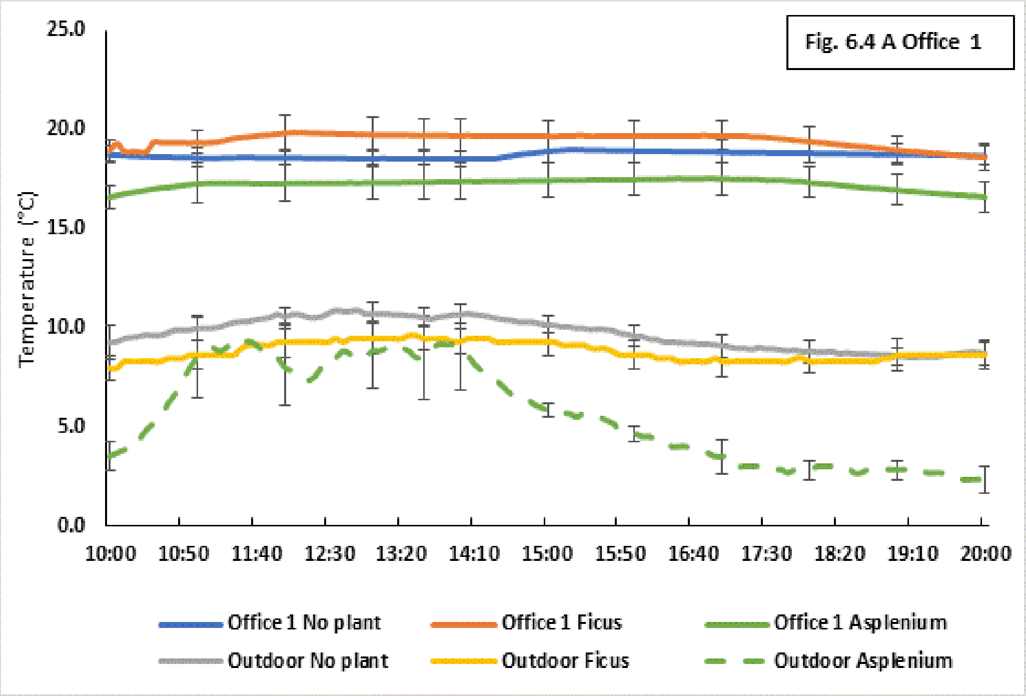


Figure 6.3 A and 6.3 B: A comparison of the mean AH during the winter 2109 experiments within Office 1 (Figure 6.3 A), Office 2 (Figure 6.3 B) and outdoors. Where: ' No plant', represents the AH within each office on the test days with no plants and , '*Ficus*' or '*Asplenium*' represents the days with plants in the office respectively. Outdoor No plant, *Ficus* or *Asplenium* represent the outdoor AH on the same days. Data are the means of three days of repeat measurements per condition (N=3) ± SEM.

When taking account of the different starting concentrations and comparing the change in AH from 10:00-13:30 and 10:00-17:30, the p-values of the f the ANOVA and post hoc Tukey's tests were all greater than 0.05, which shows there were no significant differences in the change in AH concentration within Office 1, on the days with either *Ficus* or *Asplenium* plants in the office compared to the days without plants). Within Office 2, the changes with either *Ficus* or *Asplenium* plants were significantly different compared to the days without plants ($p<0.05$), but this difference is most likely explained by the higher starting AH and sharper fall in AH concentration on the days with No plants rather than a significant increase in AH on the days with plants.

The changes in T_a are shown in Figures 6.4A and 6.4B. The T_a within both offices remained stable throughout the working day, typically with only 1°C variation between 10:00 and 17:30. Office 1 was cooler than Office 2 on all test days, and it was significantly cooler in Office 1 on the test days with *Asplenium* plants compared to the days with *Ficus* plants ($p<0.05$). During the Plant 2 test days (*Asplenium* plants in Office 1 and *Ficus* plants in Office 2) both the indoor and outdoor T_a were significantly lower compared to the No plants and Plant 1 test days (*Ficus* plants in Office 1 and *Asplenium* plants in Office 2), which also corresponds with lower AH shown in Figures 6.3 A and B. Temperature rises were accompanied by a fall in RH (data not shown).



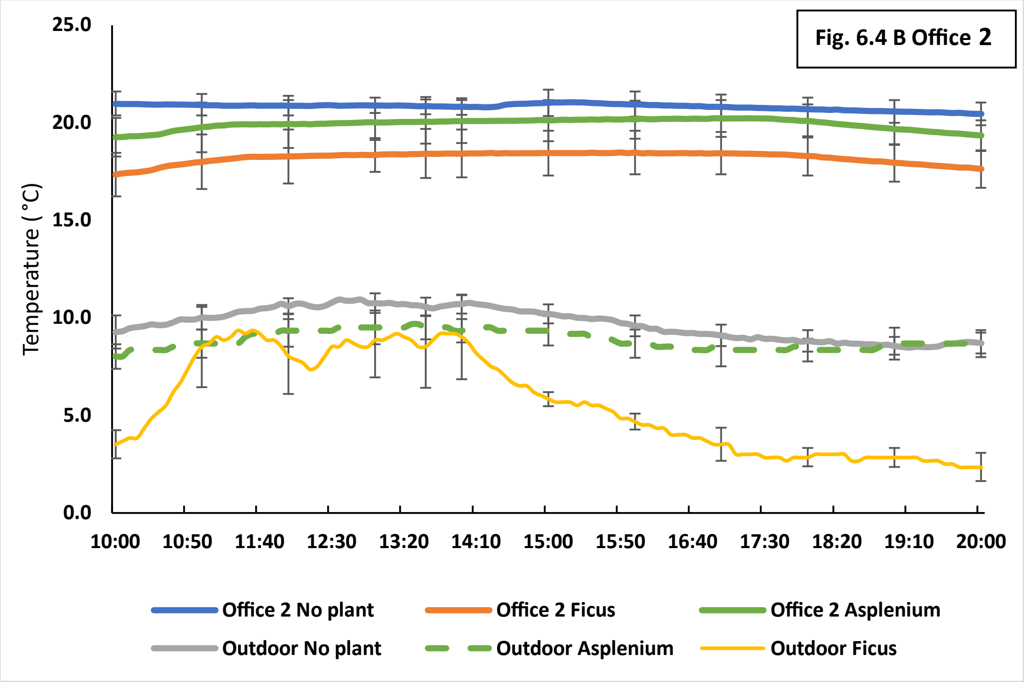


Figure 6.4 A and 6.4 B: A comparison of the mean T_a during winter 2019 within Office 1 (Figure 6.4 A), Office 2 (Figure 6.4 B) and outdoors. Where: Office 1 or Office 2 No plant, *Ficus* or *Asplenium* represents the T_a within each office on the test days with either no plants, twelve *Ficus* or six *Asplenium* plants in the office respectively. Outdoor No plant, *Ficus* or *Asplenium* represent the outdoor T_a on the same days. Data are the means of three days of repeat measurements per condition (N=3) ± SEM.

6.3.2 Spring 2019

During springtime, the mean daytime indoor AH within Office 1 across all test days ranged between 8.6 -13.1 g m^{-3} and was significantly higher (28-60 % higher) than outdoors for all time periods where the outdoor AH ranged between 6.7 - 8.1 g m^{-3} as shown in Figure 6.5.

The mean outdoor AH at the start of the test days without any plants in the office was 7.1 g m^{-3} compared to 8.1 g m^{-3} (14 % lower) on the days with plants in the office. However, unlike the indoor AH, the outdoor AH dropped significantly during the daytime, to reach the lowest AH concentration around 15:00 on the days with plants in the office whereas it increased marginally on the days with no plants in the office.

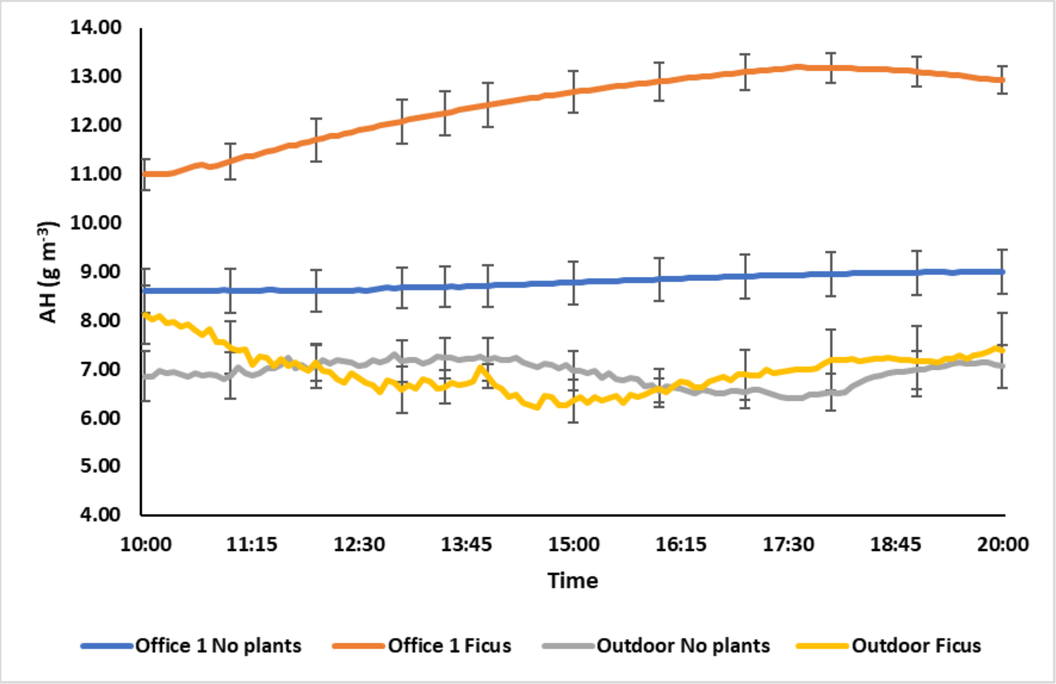


Figure 6.5: A comparison of the mean indoor and outdoor AH during spring 2019 for Office 1. Where: "Office 1 No plant" and "Office 1 *Ficus*" represent the AH within the office on the test days with either no plants or twelve *Ficus* plants in the office respectively. "Outdoor No plant" and "Outdoor *Ficus*" represent the outdoor AH on the same days. Data are the means of six days of measurements per condition (N=6) ± SEM.

During the test days with *Ficus* plants in the office the AH was significantly higher, typically by 20-30%, than on the days without plants. The mean indoor starting AH at 10:00 on the days with No plants was 8.6 g m^{-3} and this steadily increased during the day, by lunchtime (13:30) the AH had increased to 8.7 g m^{-3}, and by the end of the working day (17:30) the mean AH was 8.9 g m^{-3}, an increase of 3.5% over the course of the day. By comparison, during the days with plants in the office the mean starting AH was 11.0 g m^{-3}, which increased to 12.3 g m^{-3} by lunchtime and 13.2 g m^{-3} by 17:30, an increase of 20% over the course of the day.

To account for the differences in the starting concentrations of AH, the changes in AH during the day were compared. The two-way, paired t-tests showed the AH within office 1 increased significantly on the days with plants in the office compared to the days without plants, between 10:00–13:30, ($p<0.05$) and between 10:00-17:30, ($p<0.001$). In contrast, when comparing the change in the outdoor AH, the paired t-tests showed there was a significant reduction in AH on the days with plants in the office compared to the days without plants, between 10:00 -13:30, (p<0.05), but no significant difference in the AH change between 10:00 -17:30, since the p-value is greater than 0.05. The change in indoor AH on the days with plants in the office is not therefore attributed to the change in outdoor AH.

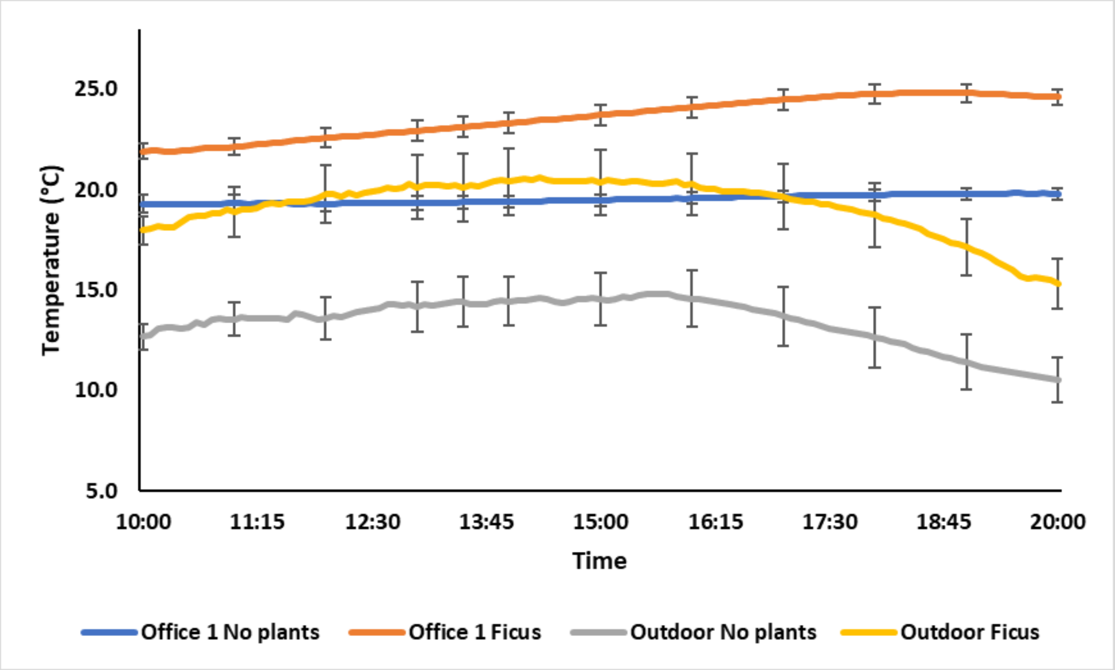


Figure 6.6: A comparison of the mean indoor and outdoor T_a during spring 2019 for Office 1. Where: "Office 1 No plant" and "Office 1 *Ficus*" represent the T_a within the office on the test days with either no plants or twelve *Ficus* plants in the office respectively. "Outdoor No plant" and "Outdoor *Ficus*" represent the outdoor AH on the same days. Data are the means of six days of measurements per condition (N=6) ± SEM.

Figure 6.6 shows the mean indoor T_a followed a similar pattern to that of the AH, rising from the start of the day and reaching a maximum of 24.8 °C between 17:30-18:30. The outdoor T_a followed a similar pattern of rising during the day, but it reached the peak T_a earlier than indoors, between 14:30-16:00, it fluctuated more than the indoor T_a and was typically 30-60 % lower. It was significantly warmer in the office, and there was a significantly greater increase in the mean indoor T_a on the days with plants compared to the days without plants in the office, between 10:00-13:30 and 10:00-17:30 ($p<0.05$ and $p<0.001$ respectively). There was no significant difference in the change in the outdoor temperatures on the days with plants compared to the days without plants for the same time periods.

6.3.3 Summer 2019

During summer 2019, the average daytime indoor AH within Office 1 was higher than during winter or spring and ranged between 13.3-14.5 g m^{-3} across all test days (10-50% higher). It was also significantly higher (typically by 30-43 %) and more stable than the outdoor AH for all time periods where the mean outdoor AH ranged between 9.3-10.0 g m^{-3} as shown in figure 6.7. The large standard error bars (± 0.4-0.7 SEM) associated with the mean outdoor AH illustrate the wider variation outdoors compared to the indoor AH (± 0.3-0.5 SEM).

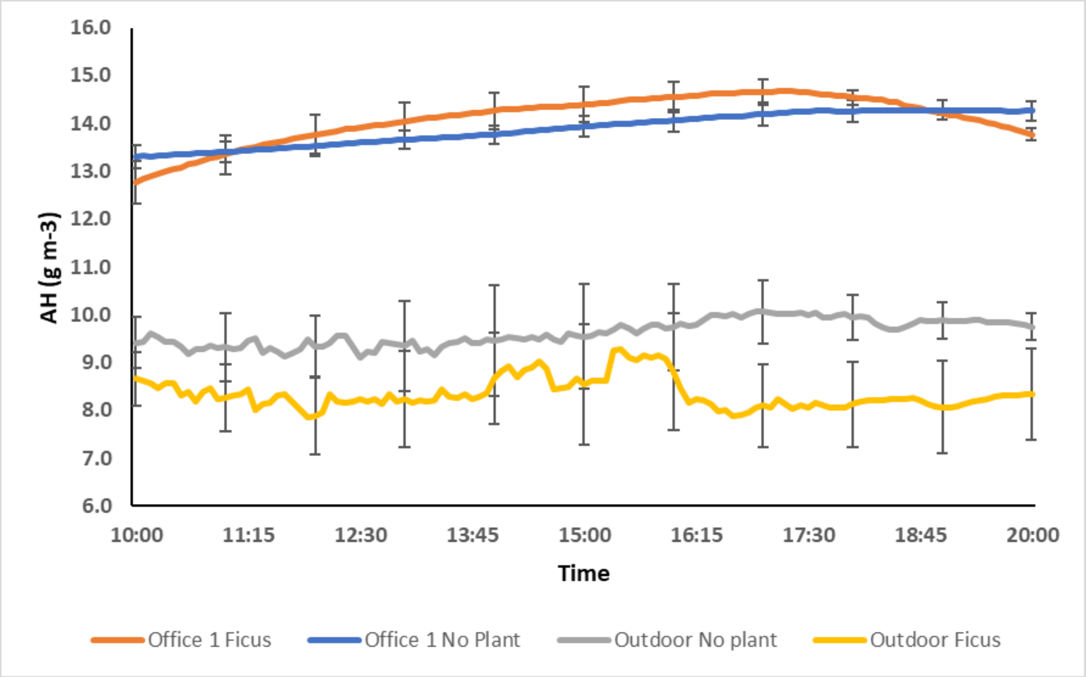


Figure 6.7: A comparison of the mean indoor and outdoor AH during summer 2019 for Office 1. Where: "Office 1 No plant" and "Office 1 *Ficus*" represent the AH within the office on the test days with either no plants or twelve *Ficus* plants in the office respectively. "Outdoor No plant" and "Outdoor *Ficus*" represent the outdoor AH on the same days. Data are the means of three days of measurements per condition (N=3) ± SEM.

The mean indoor AH at the start of the day (10:00), was comparable on the days with and without plants in the office, with values of 12.8 g m^{-3} and 13.3 g m^{-3} respectively. The AH increased steadily during the day, at lunchtime the mean AH had reached 14.2 g m^{-3} and 13.7 g m^{-3} on the days with and without plants and by the end of the working day (17:30) the AH had increased to 14.6 g m^{-3} and 14.3 g m^{-3} on the same days respectively (5% higher on the days with plants).

The indoor AH was higher on the days with plants compared to the days without plants, but there was also more variation across the test days and the two-way paired t-tests t after 3.5 h (p=0.09) or 7.5 h (p=0.28) showed the increase in AH was not statistically significant on the days with plants compared to the days without plants in the office. There were also no significant differences in the changes in the outdoor AH after 3.5 h or 7.5 h on the days with or without plants in the office as shown by all p-values being greater than 0.05. The large error bars show the significant variation which occurred in the outdoor humidity both between the test days and throughout the day.

A comparison of the change in T_a during the days with and without plants in the office are presented in Figure 6.8.

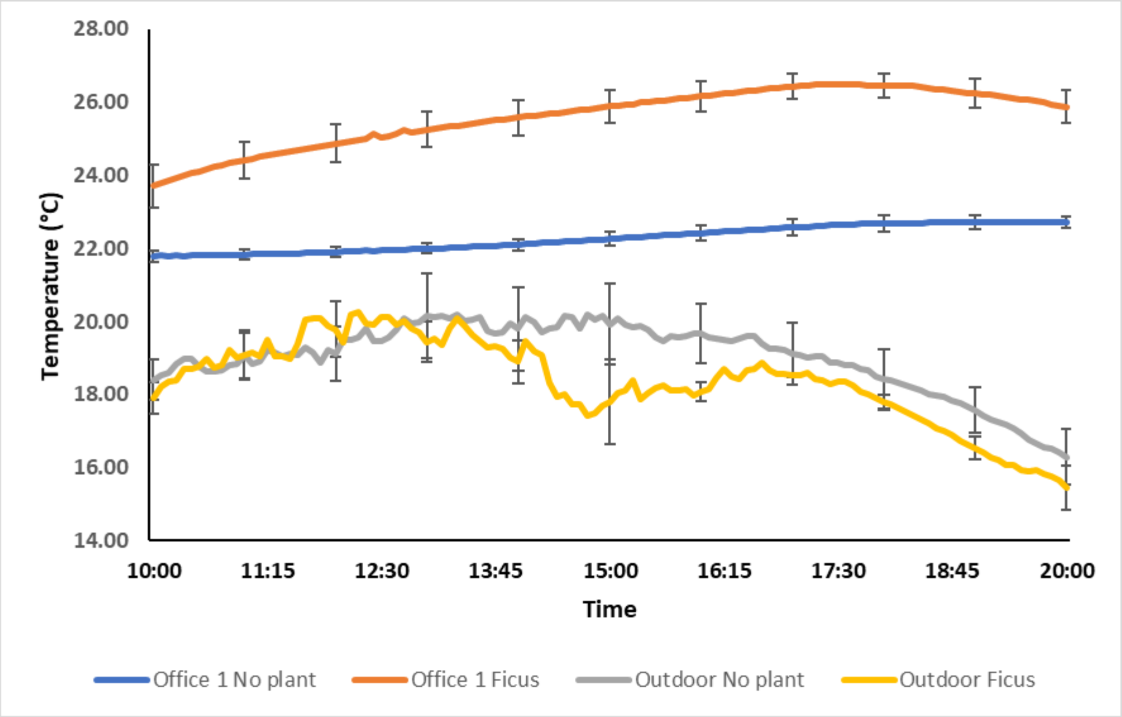


Figure 6.8: A comparison of the mean daytime indoor and outdoor T_a during summer 2019, for Office 1 on the test days with either twelve *Ficus* plants or No plants in the office. Data are the means of three days of measurements per condition (N=3) ± SEM.

The T_a at the start of the experimental days with plants in the office were typically 2°C warmer than the days without plants, ranging from 23.0-24.5 °C compared to 21.4-22.0 °C. The T_a rose steadily during the day and on the days with plants it reached a peak of 26.5 °C (± 0.18). The paired t-tests showed the rise in indoor T_a was significantly greater on the days with plants compared to the days without plants in the office after 3.5 h and 7.5 h (all $p < 0.05$).

The outdoor T_a at 10:00 was comparable across the days with plants and without plants in the office ranging between 17.6 °C-19.7 °C, but it fluctuated significantly during the day and the large SEM highlights the variation across the test days. The p-values of the paired t-tests were greater than 0.05, confirming the differences in outdoor T_a change between the plant and No plant days were not significant.

6.3.4 Winter 2021

During winter 2021, experiments were conducted in offices 1 and 3 which were adjacent to each other and when the central heating was set to working day regime and would therefore automatically heat the offices to maintain a minimum of 19 °C during the working day. Six *Epipremnum* plants were introduced into office 1 on the plant test days.

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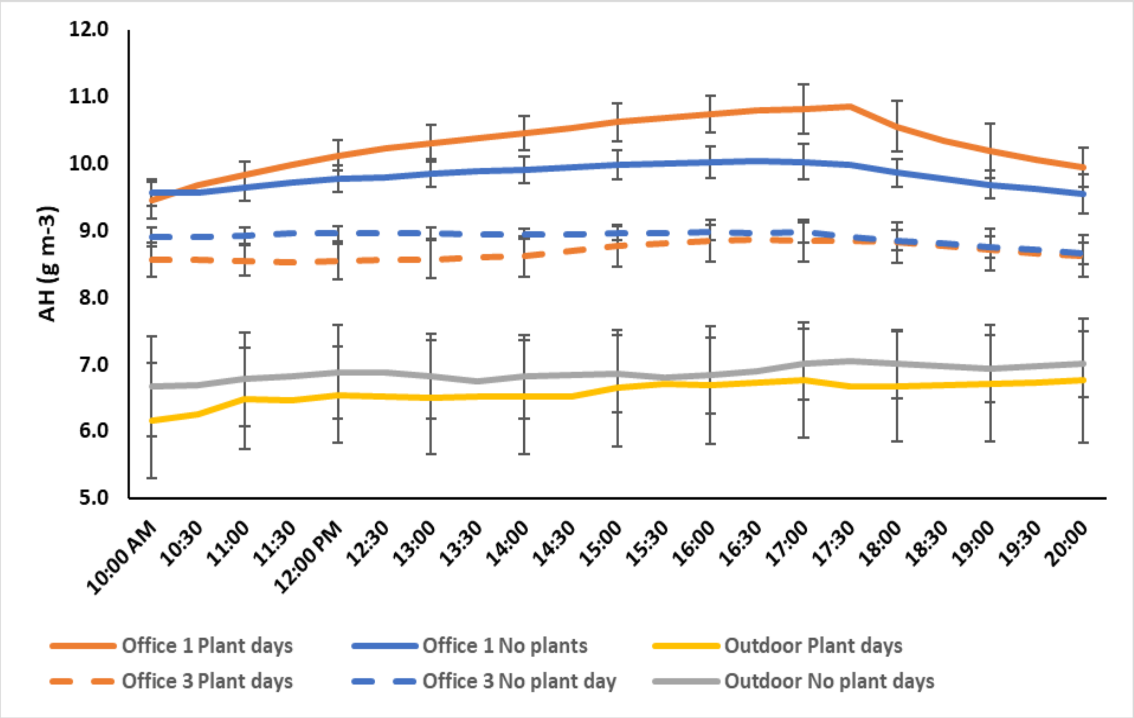


Figure 6.9: Comparison of the mean indoor and outdoor AH during the test days in January 2021.

"Plant days" refer to the test days when six *Epipremnum* plants were present in Office 1 but no plants in Office 3 (the control). "No plants" refers to the test days with no plants in either office. "Outdoor No plant" and "Outdoor Plant days" represent the outdoor AH on the same days. Data are the mean of 5 days of measurements per condition (N=5) ± SEM.

Figure 6.9 shows the mean daytime indoor AH within both offices ranged between 8.6 -10.9 g m^{-3} and was consistently 40-50% higher than outdoors. The indoor AH was also more stable across the test days as shown by the SEM which ranged between ± 0.1- 0.4 g m^{-3} for the indoor AH and ± 0.5-0.9 g m^{-3} for the outdoor AH.

Although office 1 had a consistently higher AH than office 3 (3-24 % higher) with no plants in the office, the indoor AH within both offices followed a typical pattern of remaining stable and showing only a small rise during the day to a peak around 17:30 when the office door was opened, and the lights were turned off. On the days without plants in either office, the mean indoor AH at the start of the day (10:00) in office 1 was 9.5 g m^{-3} which had increased to 9.9 g m^{-3} and 10.0 g m^{-3} by 13:30 and 17:30 respectively, an increase of 5% by the end of the working day. For the same time periods, the mean AH within office 3 started at 9.2 g m^{-3} and increased to 9.3 g m^{-3} by 13:30 and remained at this concentration until 17:30, an increase of 1% over the working day. On the days with plants in Office 1 the mean AH had increased by 10% by lunchtime and 15% at the end of the working day (from 9.5 g m^{-3} to 10.9 g m^{-3} between 10:00 and 17:30). By comparison within Office 3, which had no plants, the AH remained constant between 8.6 g m^{-3} and 8.8 g m^{-3} throughout the day.

The two-way paired t-tests confirmed the increase in AH within Office 1 was significantly greater on the days with *Epipremnum* plants in the office compared to the days without plants after 3.5 hours and 7.5 hours (all $p<0.05$) and significantly greater than the changes in office 3. In Office 3, which had no plants for all tests, there was no significant differences in the AH change over the same test days after 3.5 or 7.5 hours.

The offices were well insulated and with the central heating in operation, the indoor T_a during working hours were maintained within a comfortable range, the mean T_a ranging between 19.5-21.9 °C for both offices across all the test days. This was consistently more stable, and 10-15 °C warmer than outside, which ranged between 4.5-7.1 °C as shown in Figure 6.10. The central heating also helped to maintain the indoor daytime T_a typically 2-3 °C higher during the winter 2021 experiments compared to winter 2019, when the mean daytime T_a ranged between 16.6 - 19.7 °C.

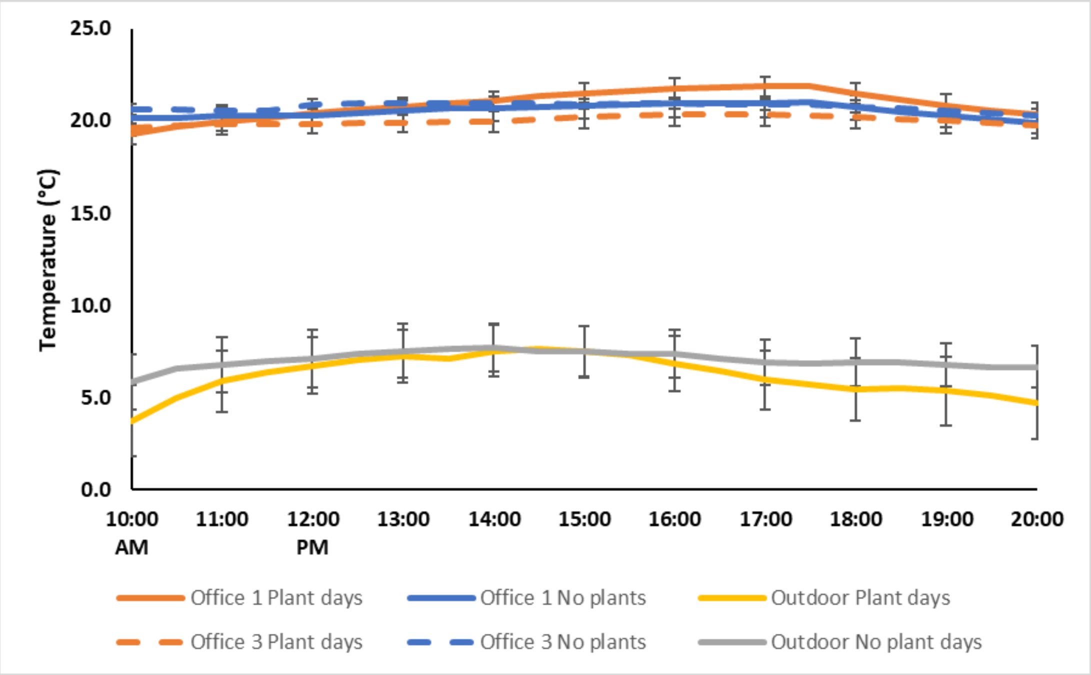


Figure 6.10: A comparison of the mean indoor and outdoor temperatures during winter (January) 2021, for Office 1 and 3 . "Plant days" refer to the test days when six *Epipremnum* plant were present in Office 1 but no plants in Office 3 (the control) and "No plants" refers to the test days when there no plants in either Office 1 or Office 3. Data are the means of five days of repeat measurements per condition (N=5) ± SEM.

The T_a followed a similar diurnal pattern in both offices of rising steadily during the daytime to reach a peak around 17:30 after which it fell overnight. The outdoor temperature also increased during the day, but it peaked earlier, typically between 14:30 -15:30. On the days without plants the T_a rose from 19.5 in office 1 and 20.2 °C in office 3, to 21.0 °C in both offices by 17:30 an increase of 7.7 % and 5% respectively. By comparison on the days with *Epipremnum* plants in office 1, the temperature increased by 11% from 19.9 - 20.3 °C whereas it only rose by 2.5 % from 19. 8 -20.3 °C in Office 3.

All p-values of the paired samples t-tests were greater than 0.05 which showed there were no significant differences in the T_a changes between 10:00 and either 13:30 or 17:30 within Office 1 or Office 2 on the days with plants compared to the days without plants.

6.3.5 The variation in ET rates of the plants

To investigate the effect of varying office environments and seasonal conditions of T_a and RH on plant ET rates, measurements of the ET rates during each set of seasonal experiments in different offices are presented in Figure 6.11. The mean daily VPD was calculated for each set of experiments using Equation 5.1 (Chapter 5) and is displayed within the legend box.

For *Ficus* plants which were measured in the same office over different seasons, the total amount of water lost per day through ET increased steadily from winter through to summer, with a 26% and 64% greater ET in spring and summer 2019 compared to winter 2019, respectively. In winter 2019, twelve *Ficus* plants contributed an average of 422 g water vapour per day (35 g plant^{-1} day^{-1}), in spring 531 g day^{-1} (44 g plant^{-1} day^{-1}) and in summertime 696 g day $^{-1}$ (58 g plant^{-1} day^{-1}).

The paired t-tests confirmed the differences in ET rates between the seasons were statistically significant (all p<0.001). There was no significant difference between the *Ficus* ET rates in Office 1 or Office 2 during winter 2019 (p=0.77). For *Asplenium* plants during winter 2019, the water losses in Office 2 (35 g plant^{-1} day^{-1}) were comparable to those of *Ficus* but the water losses were significantly lower in office 1 (24 g plant^{-1} day^{-}1) compared to Office 2 (p<0.001), this corresponded with a lower VPD in Office 1 during the *Asplenium* test days. *Epipremnum* plants during winter 2021 had the highest ET rate per plant out of all the plants tested. Six *Epipremnum* plants contributed on average a total of 399 g moisture to the office per day (67 g plant^{-1} day^{-1}).

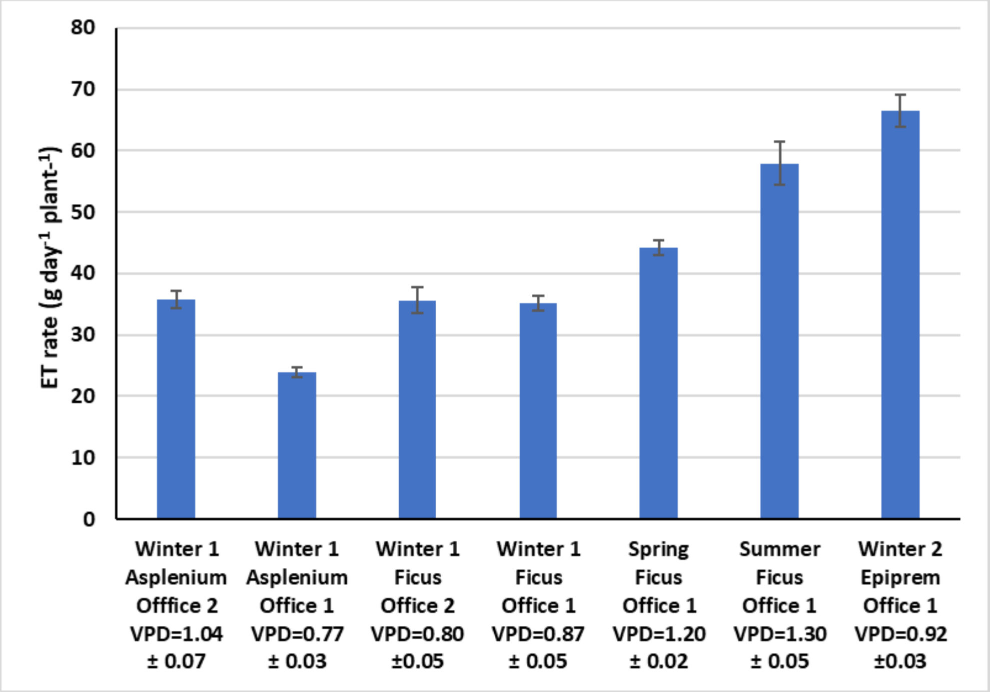


Figure 6.11: A comparison of the mean ET rates of different plant species measured during the test days within office 1 or 2, for *Asplenium*, *Ficus* or *Epipremnum* species during winter, spring or summer. For Winter 1 (winter 2019), data are the means of 12 replicate *Ficus* plants or six replicate *Asplenium* plants over 3 repeat test days, (N= 36 and N=18 respectively). For Spring

(2019) data are the means of 12 replicate *Ficus* plants and 6 repeat test days (N=72). For Summer (2019) data are the means of 12 *Ficus* plants over three repeat days (N=36). In Winter 2 (winter 2021) data are the mean of 6 replicate *Epipremnum* plants and 5 repeat test days (N=30). Bars represent means ± SEM. The daily VPD (kPa) is the mean of the 24-hour average for each set of repeat test days ± SEM.

The ET rates of all plants were higher in the environmental chambers (Chapter 5) than in the offices for comparable conditions of daytime T_a and RH. In the chambers, *Ficus* plants released between 65 -89 g plant^{-1} day^{-1}, *Epipremnum* plants 134 -182 g plant^{-1} day^{-1}, and *Asplenium* plants 76 -105 g plant^{-1} day^{-1}. Thus, the ET rates, were one and half to three times greater in the environmental chambers compared to the offices.

6.3.6 Contribution of plants to indoor AH

To investigate in more detail how the water vapour lost from the plants through ET may have influenced the actual AH within the office, the approximate water vapour released from the plants versus the change in moisture content within the room was examined on an hour by hour basis during a 24-hour period and an example is provided in Figure 6.12.

The water vapour contribution from the plants was determined by applying the percentage weight loss per plant for each hour measured in the chamber experiments in Chapter 5 and multiplying this by the 24 hour weight loss measured in the offices for 6 plants. The actual increase in water vapour concentration in the office is determined from the hourly difference in the AH measured in the office for the same time period.

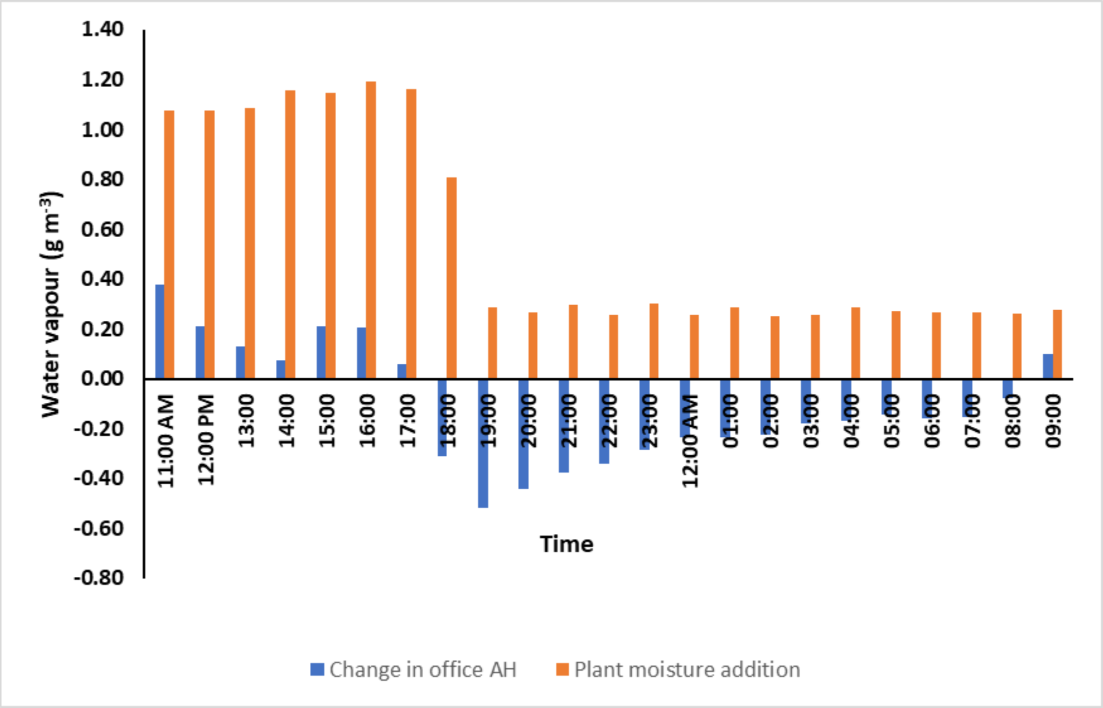


Figure 6.12: A detailed example comparing the hour by hour change in absolute humidity (g water vapour m^{-3}) within Office 1 on a day with plants in the office, against the hour by hour water vapour released via evapotranspiration from six *Epipremnum* plants at the same time (g water vapour m^{-3}) on 28th January 2021. ET rate is determined from the weight loss of the plant, it is assumed that the weight loss from the plants is all water vapour, and that all of this is added to the indoor air within the office.

Figure 6.12 shows the AH within the office increases each hour from 10:00 until approximately 18:00 when the door is opened, and the lights are turned off. When the door is opened air from within the room is exchanged with the corridor air and measurements showed the AH of the corridor (data not shown) was approximately 2 g m^{-3} lower than the air within the office at the same time, hence the AH in the office falls as the AH concentration equilibrates. The room AH concentration continues to fall during the night. Based on the findings of chapter 5, the moisture emitted by the *Epipremnum* plants is highest during the daytime when the lights are on and reduces significantly when the lights are turned off. The hourly increase in moisture content of the air within the office is significantly less, between 0.4 g m^{-3} and 1.95 g m^{-3} lower over 24 hours, than the approximated moisture emitted by the plants The difference can be explained by moisture being removed through the air exchange or being absorbed by the materials within the room and this is examined in more detail below, between 65% and 100% of the water vapour emitted by the plants was lost in this way.

6.3.7 Comparison of the theoretical moisture contribution determined from a moisture balance model and the actual moisture change in Office 1

Using the moisture balance equation 6.2, assuming the moisture sorption is constant and there were no other sources of moisture production in the offices, the moisture production rate of the plants can be theoretically calculated, and the results are shown in Table 6.2.

Using the data for the AH concentrations for the indoor and outdoor air, measured for the 7.5-hour period between 10:00 and 17:30, for each test day the hourly moisture production rate per cubic metre (g h^{-1} m^{-3}) within each office was estimated using equation 6.2. The air flow rate (Q) was calculated from the ACH determined for each office in Chapter 4. The difference in the average moisture production rate for the test days with plants in the office minus the rate for the days with no plants in the office was calculated and is shown as “moisture excess” in Table 6.2. Assuming the moisture adsorbed or desorbed by the materials in the room remains constant, then the difference between the Plant and No plant days should be due to the moisture emitted by the plants.

To compare the estimated moisture change determined from the model against the actual moisture change in the room, the mean hourly change in AH measured within each office was determined for the period 10:00–17:30 for the same Plant and No plant test days and the difference between the plant and No plant test days is shown in Table 6.2 as actual moisture excess.

The actual moisture emitted by the six plants for the same time periods, calculated from the total weight loss of the plants as described above (section 6.3.7) is also included in Table 6.2.

The moisture excess determined from the moisture balance models was higher than the actual measured increase in moisture content within the room, but within the standard errors associated with the means. Although the model overestimated the moisture excess compared to the actual data both sets of results showed the same order of seasonal moisture production and excess, where the moisture production was lowest in winter then summer and the highest was in spring.

	Calculated moisture excess **g h^{-1} m^{-3}**	**Actual moisture excess** **g h^{-1} m^{-3}**	**Moisture emitted by plants** **g h^{-1} m^{-3}**
Winter 2019 **Office 1** **Plants = Ficus**	-0.05 (±0.09)	-0.02 (±0.08)	1.2 (±0.02)
Winter 2019 **Office 2** **Plants = Ficus**	0.08 (±0.08)	0.06 (±0.09)	1.2 (±0.03)
Spring 2019 **Office 1** **Plants = Ficus**	0.67 (±0.12)	0.25 (±0.02)	1.5 (±0.02)
Summer 2019 **Office 1** **Plants = Ficus**	0.55 (±0.09)	0.12 (±0.04)	2.0 (±0.06)
Winter 2021 **Office 1** **Plants =Epipremnum**	0.17 (± 0.16)	0.11 (±0.02)	1.13 (±0.02)
Winter 2021 **Office 3** **No plants**	0.01 (±0.08)	0.02 (±0.02)	0.00

Table 6.2: A comparison of the difference in the moisture generation calculated using moisture balance models and the actual measured changes of air moisture content within the office, and the total water vapour emitted by the plants for each season. Data are the means of multiple days of repeat measurements per condition, in winter and summer 2019, (N=3) ± SEM, in spring 2019 (N=6) ± SEM and in winter 2021 (N=5) ± SEM.

Models assume perfect and uniform mixing of the air and in this calculation they do not account for the absorption by the walls and materials in the room (Hens, 2013; IEA, 1991). In addition, the model also assumes that all the air exchange is made with the outdoor air, whereas in reality some of the air exchange is made between the office and the air in the corridor through the gaps around the internal door, and the indoor air has a higher AH than the outdoor air.

6.4 Discussion

All plant species contributed water vapour to the indoor air within the three offices used in these experiments, as shown by the water loss/ET from the plants, but there was a seasonal variation. The water loss from the plants increased progressively from winter through to summer with 12 *Ficus* plants contributing 422 g moisture day $^{-1}$ (35 g plant^{-1} day^{-1}) in winter and 696 g day $^{-1}$ (58 g plant^{-1} day^{-1}) in summer. The seasonal increase in moisture contribution corresponded with increasing daytime T_a, higher light intensity and daylight hours, and an increasing VPD within the office. This supports the findings from the experiments in the environmental chambers in chapter 5 which showed that ET rate had a positive linear relationship with VPD and temperature. Plant activity (photosynthesis and transpiration) has also been shown to respond to seasonal changes in day length, light intensity and light wavelength and colder nights (Cai et al., 2020; Li et al., 2019; Salisbury & Ross, 1992) which helps to further explain the variation in ET rates.

There were significant differences in the ET rates between plant species. When comparing the ET rate of *Ficus, Asplenium and Epipremnum* in the same office during winter, *Epipremnum* was found to have significantly the highest ET rate per plant (66.5 g plant^{-1} day^{-1})($p<0.05$). This supports the findings from Chapter 5, where *Epipremnum* species was found to have the highest ET rate in the environmental chambers. The higher ET rate in *Epipremnum* is partly explained by the plants having a 40% and 62% higher leaf area than *Ficus* and *Asplenium* respectively and as stomata are found in the leaves this would increase the number of stomata available for plant transpiration (Chapter 3). Additionally, previous studies have shown that *Epipremnum* has a high stomatal density which has a positive linear correlation with ET rate (Panyametheekul et al., 2019). The experiments involving *Epipremnum* were also conducted during winter 2021 when the room T_a and VPD were slightly higher (VPD 15% higher) than for the experiments with *Ficus/Asplenium.* Both factors are associated with higher ET rates (results from Chapter 5)(Grossiord et al., 2020; Massmann, Gentine, & Lin, 2019; Turner, 1991) and the environmental conditions are therefore also likely to have contributed to the higher *Epipremnum* ET rates. In previous research of indoor plants in an office environment, Gubb et al. (2018), measured ET rates of 28 -71 plant^{-1} day^{-1} for a range of species, which are comparable to the rates measured here.

The ET rates of the plants measured in the offices were lower than those measured in the environmental chambers, although the order of magnitude of ET rates between species was the same. The difference is most likely due to better light provision; the chambers had a higher, more consistent light intensity and the light source was directly above the canopy evenly spread across the plants, all of which would contribute to higher photosynthesis and transpiration rates

(Dominici et al., 2021; Gubb et al., 2018; Torpy, Irga, & Burchett, 2014). In addition there may have been a difference in air flow in the chambers compared to the office, as although both environments had a very small air flow, in the chambers the air flow is necessary to maintain the RH within the settings for the environmental parameters.

One of the main aims of this chapter was to determine if indoor plants significantly impacted the ambient moisture content within an office environment during the hours of the working day. This is a complex issue as there are a many interacting factors which affect the moisture content within a room and the first step was to compare the change in moisture content in the same office with plants and without plants.

The T_a and AH in the office were notably higher (10-50%) during the summer compared to winter or spring but there was no significant difference in the rise in AH between the days with or without plants A post-hoc power analysis using G*Power was conducted using the data from the paired tests for the change in AH over 7.5 h, using p-0.05, an effect size of 1.38 (determined from the data) and this revealed the power of the tests was 26% which is low compared to Cohens recommendation of 80%. Thus the sample size may have been too small to detect a significant difference.

During winter 2019 with the central heating set to low, the introduction of 12 *Ficus* or six *Asplenium* plants did not lead to any significant differences in the AH within office 1 or office 2 compared to the days without plants. During spring 2019, and winter 2021 the increase in AH concentration was significantly higher on the days with plants in the office (12 *Ficus* plants were used in 2019 or 6 *Epipremnum* plants in 2021), compared to the days without plants and increased steadily through the day to reach a peak between 17:00-18:00 ($p<0.05$). On these days the AH concentration had increased significantly by lunchtime and continued to rise until late afternoon.

The above findings do not take account of variations in ACH, outdoor T_a, AH and ACH over the different experimental days although these are known to have a significant influence on the moisture concentration (Glass & Tenwolde, 2009; Awbi, 2003). When moisture balance equations were used to take account of these factors, the results showed that in spring 2019, summer 2019 and winter 2021 the mean moisture generated in the office between 10:00 -17:30, was significantly higher on the days with plants in the office compared to the days without plants ($p<0.05$). There was no difference in winter 2019 for office 1 or office 2.

For all seasons the increase in AH concentration within the office was considerably lower than the amount of water vapour emitted by the plants. For example, in summer an average 31% more water vapour was added by the plants to the room compared to spring, but the actual increase in AH concentration within the office was 26% lower than during spring. The main difference between the two sets of experiments was that office 1 had a higher ACH rate during the plant test days in summer compared to spring, thus although more moisture was added to the office during the summer, more of this moisture was removed due to the higher ACH rate. In addition to removal through air exchange, the AH within a room is also affected by the moisture that is absorbed/desorbed by the building fabric and interior materials. Although it is not possible to quantify the amount or time of moisture sorption from this study, previous research has shown that moisture adsorption begins thirty minutes to two hours after the moisture generation and increases with increasing RH (Hens, 2013; IEA, 1991).

During transpiration, when changing liquid water within the plant to the transpired vapour, plants use sensible heat and convert it to latent heat, eliciting a cooling effect in the surrounding air (e.g. (Moss et al., 2019)). However, there was no evidence from these studies that the plants had any measurable cooling effect within the offices. Generally, the indoor T_a was stable through the working day but during spring and summer the rise in T_a was higher on the days with plants in the office compared to the days without plants. On these days there was also a rise in the outdoor T_a. Whilst there may have been a cooling effect from the plants this is likely to have been very small, localised around the leaves of the plants and insignificant compared to the heat gains from other sources such as the central heating, lighting and electrical equipment and increases in the outdoor T_a. Studies in outdoor environments, have shown that plants and trees can make significant contributions to air cooling due to a combination of shading and transpiration effects and cooling effect varied with species (Deng et al., 2020; Thomsit-Ireland et al., 2020; Perini, Magliocco, & Giulini, 2017; Cameron, Taylor, & Emmett, 2014). The differences between indoor and outdoor cooling effects are readily explained by the difference in outdoor environmental conditions (lighting, wind speed, T_a and RH), size and leaf areas of the plants.

Other research studies have reported varying impacts on room T_a and humidity by indoor plants (Tudiwer & Korjenic, 2017; Su & Lin, 2015; Torpy et al., 2013; Smith, Tucker, & Pitt, 2011; Wood et al., 2006) but the experimental parameters have varied and the ventilation rates were not specified, making it difficult to make direct comparisons of the results. Findings from a study by Su and Lin (2015), partially support our findings as they reported 10% increase in RH within a room when *Asplenium nidus* plants were introduced, but contrary to our study they measured a 1.5°C reduction in T_a in a room of 39 m^3 volume. However, they calculated the mean T_a over 24 hours which would include the reduction in room T_a typically observed overnight and reduce the mean T_a whereas this present study focussed on changes during the daytime. In addition, Su and Lin's study used 189 potted plants which is considerably more than this study and the influence of the infiltration rate and outdoor T_a on their results were not included. Researchers in Spain observed average T_a decreases of 4 °C and up to 15% increase in RH when a passive indoor living wall was introduced into a University hall (Fernández-Cañero, Urrestarazu, & Franco Salas, 2012). Further experiments highlighted the effect of air circulation on humidification impact as the researchers showed that increasing the air flow through the substrate and plants, increased the cooling and humidification effect near the living wall, but the effect was not sustained after the fan in the active living wall was turned off (Pérez-Urrestarazu et al., 2016).

The findings from a study of a passive green wall in a classroom, reported an increase in RH in the greened classroom but no impact on T_a and the study also showed that occupants were more comfortable in the greened classroom in winter (Tudiwer & Korjenic, 2017). When mechanical ventilation is in operation in the room, some studies have shown the presence of plants has had no impact on the RH or T_a (Mangone, Kurvers, & Luscuere, 2014; Wood et al., 2006) whereas others have reported small increases in RH (Torpy et al., 2013; Smith & Pitt, 2011; Lohr & Pearson-Mims, 1996). However, these studies were conducted with occupants in the offices and the moisture removal by the HVAC system was not specified, it is therefore difficult to assess the true impact of the plants on the indoor humidity.

Throughout all experiments in this study, with the doors, windows and trickle vents closed, the mean indoor daytime RH ranged between 50-71% RH and the mean T_a was between 17.5-26.5°C. The T_a meets the requirements for the minimum working T_a (Health and Safety Executive, 1992) but during the summertime the T_a and RH exceed or at the limit of the UK recommendations (British Standards, 2011; CIBSE, 2006b). The thermal comfort of occupants was not investigated in this study, but working in the offices with the doors, the trickle vents and windows closed is not recommended for the comfort of building occupants.

The risk of mould growth occurs if the average RH within a room stays above 70% for several days (British Standards, 2011). During these experiments, levels of RH above 70% were only measured for a few days during the daytime in summertime, therefore no risk of mould growth was identified. In this study, the addition of plants did not increase the humidity levels sufficiently to increase the risk of mould growth.

A study in Australia by Torpy et al. (2013) of 55 offices, found that the addition of indoor plants had no significant impact on either the mould spore count or the species composition within the offices and mould count was significantly higher outdoors than indoors. In our study, the extensive trees and vegetation surrounding the building are likely to have a much greater impact on the indoor mould spores than indoor plants. However, due the building design and the low ACH rate of the offices, during sustained periods of high outdoor humidity or if the offices are used without the trickle vents or windows opened, there is a potential risk of mould growth within the building. The risk will increase when the building is occupied as people contribute significant amounts of moisture to the indoor air. Further monitoring of the indoor T_a and RH within the building, over longer periods is recommended to better understand the risk of mould growth.

During most of the experiments, the T_a and RH within the offices were within the recommended range for human comfort. However, the conditions in the office during summertime, sometimes exceeded the levels of T_a and RH recommended for human comfort. The days of highest RH were on the days without plants in the office and therefore not caused by the plants. These studies highlight the increase in RH, and reduced IEQ which is likely to be experienced by the occupants in naturally ventilated buildings with low ACH when windows and vents are kept closed.

Irrespective of changes in T_a and humidity, previous research has shown that the presence of plants can improve people's thermal comfort during winter (Tudiwer & Korjenic, 2017; Mangone, Kurvers, & Luscuere, 2014) and their perception of air quality (Nieuwenhuis et al., 2014). The psychological benefit from adding plants to the office for people's thermal comfort and wellbeing may therefore have a more significant impact than the impact of the plants on indoor humidity.

6.4.1 Limitations of the research method and results

For consistency, the same *Ficus* plants were used throughout 2019 and pruned lightly before each set of seasonal experiments to maintain the size. The plants therefore matured over the test period and as the plant age affects its physiological activity, this could have impacted the results.

The experiments were conducted at raised CO_2 concentrations. Measurements of ambient humidity showed this did not impact the indoor AH but it may have impacted the ET rate of the plants.

The experiments were conducted over different days and although steps were taken to account for and minimise the influence of outdoor weather conditions, there was day to day variation which could not be avoided. Comparisons on different days and in different years may produce different findings. Due to limited access to the offices, the number of repeat tests was small, leading to low statistical power in the analysis of the results, to raise the statistical power, it is recommended that a greater number of repeat tests are conducted in the future.

6.5 Conclusion

This study investigated the seasonal impact of indoor plants on the moisture content and T_a of indoor office environments, in a prefabricated modular building. Measurements were made when the rooms were operated with the natural ventilation closed and the air exchange rate was very low. The findings show that the introduction of 12 *Ficus* plants or 6 *Epipremnum* plants resulted in a small but significant increase in the moisture content of an office of 28 m^3 volume, during a series of test days in spring and winter respectively, compared to the days without plants. The plants in this study emitted between 35-68 g of moisture, per plant, per day.

The amount of water vapour emitted by the plants via ET showed a significant seasonal variation and was affected by the environmental conditions within the office, with 66% more water vapour being emitted during warm summer days compared to cool winter ones. Most of the moisture emitted from the plants was removed through room air exchange and moisture sorption. Factors which affect these such as the building design, the indoor and outdoor T_a, RH and air flow determined the magnitude of impact that the plants had on the humidity within the office. These results suggest that in hot, dry indoor environments with a low air exchange, well-watered plants can make a small but significant contribution to increase in ambient air humidity. The choice of plant species can have a significant impact on the moisture contribution plants make to the indoor environment.

Chapter 7

The appearance of indoor plants and their effect on people's perceptions of indoor air quality and subjective well-being

This chapter is based on the published paper: "Berger et al., 2022. The appearance of indoor plants and their effect on people's perceptions of indoor air quality and subjective well-being. *Building and Environment*, *219*, p.109-151."

7.1 Introduction

Built environments affect our health, behaviour and mental well-being (MacNaughton et al., 2017; Bluyssen, 2010). The adverse impacts of indoor air pollution and poor thermal comfort on the health, well-being and productivity of building occupants are well documented, and as people spend more time indoors in tightly sealed buildings these concerns are rising (Kaushik et al., 2020; Jones, 1999; Fisk & Rosenfeld, 1997). People's mental well-being is also a major health concern; in the UK mental ill health is the single largest cause of disability burden and stress (Department of Health, 2011). Furthermore, depression or anxiety accounted for 55% of all working days lost due to work-related ill health in 2019/20 (Health and Safety Executive, 2020). The psychological well-being of a person depends on many factors but the indoor environment, including the indoor air quality (IAQ) and the physical design of the space, is an important influence which can be manipulated in various ways (Clements-Croome, Turner, & Pallaris, 2019). The inclusion of indoor plants has been shown to benefit both the physical and psychological well-being of building occupants, leading to reduced health complaints and sick leave (Bringslimark, Hartig, & Patil, 2007; Fjeld, 2000).

Common IAQ problems of increased concentration of carbon dioxide (CO_2) and low relative humidity (RH) have been discussed in Chapters 1-6 and although these can be controlled by mechanical ventilation systems, such systems can be expensive and energy intensive (Wolkoff, 2018a; Awbi, 2017). Plants can reduce ambient CO_2 concentration and add moisture, through CO_2 assimilation (photosynthesis) and evapotranspiration (ET) (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014; S. V. Pennisi & van Iersel, 2012) but their effectiveness within indoor environments with low light levels is still under debate (Cummings & Waring, 2019; Gubb et al., 2018). However, studies in office environments have shown that irrespective of actual changes in IAQ conditions, occupants perceived that the IAQ of the room, (Nieuwenhuis et al., 2014) and their thermal comfort (Mangone, Kurvers, & Luscuere, 2014; Qin et al., 2014) improved when plants were present.

In built environments where people lack contact with nature, indoor plants have also been shown to reduce stress and improve people's subjective well-being (SWB) (Grinde & Patil, 2009; Bringslimark, Hartig, & Patil, 2007). Laboratory studies suggest that viewing plants can reduce stress indicators such as heart rate variability and blood pressure (Choi, Park, Jung, Ji Lee, et al., 2016; Lohr, Pearsons-Mims, & Goodwin, 1996). Studies in healthcare (Dijkstra, Pieterse, & Pruyn, 2008), retail (Brengman, Willems, & Joye, 2012) and learning environments (van den Bogerd et al., 2021) have also shown stress-reducing effects of plants, which have been partially explained by the increased attractiveness of the rooms. The visual aesthetic experience of the environment is believed to affect people's perceptions, mood state, and stress levels (De Korte, Kuijt, & Van Der Kleij, 2011; Kaplan & Kaplan, 1989). Office environments with plants are typically perceived as more attractive (Nieuwenhuis et al., 2014; Larsen et al., 1998) and have been associated with higher job satisfaction (Dravigne et al., 2008). However, other studies have not found any effect of plants on mood (Shibata & Suzuki, 2002) and results on cognitive performance are varied and difficult to compare due to the wide range of tasks, tests and subjects used (Rich, 2008).

The benefits of plants within indoor environments are generally associated with occupants' viewing the plants and it is therefore important to understand how the appearance of the plant affects people's responses. The physical appearance of the plant is primarily determined by its shape, colour, texture and size. Research involving trees and flowers has shown that shape and colour significantly affect people's emotional and physiological responses (Hůla & Flegr, 2016; Muderrisoglu et al., 2009; Kaufman & Lohr, 2004; Summit & Sommer, 1999). In an assessment of flower beauty by Hůla & Flegr (Hůla & Flegr, 2016), shape was found to be more important than colour. Healthiness, bushiness and shape have been identified as key factors affecting purchasing decisions for outdoor ornamental plants (Brascamp, 1996). Despite this importance of plant shape for people's preferences and responses to outdoor plants and its dominance in characterizing the physical appearance of the plant, it has rarely been investigated for indoor plants. Plant shape was therefore a focus of this study.

The inclusion of plants within indoor environments can benefit the health and well-being of building occupants (Bringslimark, Hartig, & Patil, 2007; Fjeld, 2000). If designers, building managers and householders are to invest in plants and achieve maximum benefits for the building occupants, it is important to know how the appearance of the plant affects people's perceptions and responses. While the current evidence from experimental work in chapters 4 and 6, and other research (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014; S. V. Pennisi & van Iersel, 2012) suggest that the impact of individual potted plants on IAQ parameters at a room scale, is relatively small, we hypothesise that people's perception of a positive change might lead to indirect augmented benefits of plants for SWB. It was hypothesised that the appearance of the plant and attributes such as shape, leaf density and plant vigour will influence people's perceptions of its benefit for IAQ and SWB.

Therefore, the objectives of this chapter were:

i) To measure people's preference and response to the appearance of indoor plants displaying different physical characteristics

ii) To determine if the plant appearance and shape affects people's perception of its impact on IAQ, RH or SWB.

7.2 Methods

7.2.1 The survey

A web-based photo-questionnaire, created using Qualtrics XM software, was conducted to investigate people's preferences and responses to a range of indoor plants. People were invited to participate voluntarily through email, LinkedIn and Facebook. Respondents were told the survey was about the use of plants in building design, advised it would take around 10 minutes to complete and gave their informed consent by proceeding with the questionnaire which was approved by the University of Reading Ethics Committee, in accordance with the Helsinki Declaration of 1975, as revised in 2000.

The survey method was chosen as it has been successfully used by previous researchers to obtain quantitative responses from a large number of different respondents (Cobanoglu, Warde, & Moreo, 2001). People's response to viewing pictures of plants has been shown to be a reliable representation of people's response to live plants (Hull & Stewart, 1992). After providing information about their demographics and attitudes to indoor plants, participants were asked to view photographs of 12 individual plants and to answer the questions based on their opinion of the plant's appearance. The order of presentation of the plants was varied to minimize any ordering effects. Space was provided at the end of the survey for participants to provide any extra information or comments of their choice. Detailed example of the questions are included in Appendix 1. The comments were extracted from the survey through SPSS collated, organised and analysed by thematic analysis.

Participants assessed the appearance of each plant in terms of its aesthetics or restorative effect, using a seven-point bipolar scale comprising of six pairs of contrasting adjectives. Participants also assessed the perceived benefit of each plant for IAQ, RH and SWB on a seven-point scale from low-high, based on its appearance. The descriptors were generated from a pilot study involving 14 participants who also identified that the meaning of the terms “air quality” and “humidity” were equivalent to indoor air quality (IAQ) and relative humidity (RH), and wellbeing meant subjective well-being (SWB). Previous studies have shown that questionnaires of people’s self-reported SWB have good correlation with measurements of their physiological stress indicators such as heart rate and blood pressure (Park et al., 2016; Chang & Chen, 2005) therefore the results of this study will not only directly indicate how a sense of well-being is influenced by the appearance of the plants but also, indirectly, how the appearance of the plants might moderate physical responses. After viewing all 12 plants, participants were asked to identify their most preferred and least preferred plants. Finally, participants ranked the physical characteristics (Colour, Leaf shape, Plant shape, Leaf pattern, Texture) in order of importance, from high to low, when considering the attractiveness of indoor plants. These characteristics were identified from previous research as important in affecting people’s preference for trees and flowers (Hareli et al., 2016; Hůla & Flegr, 2016; Elsadek et al., 2013; Kaufman & Lohr, 2004). The order of presentation of the terms was randomised to avoid ordering effects.

7.2.2 The plants

The final choice of plants included in the survey (Figure 7.1) was limited to 12 to avoid participant fatigue and was based on a number of considerations summarised in Table 7.1.

All plants were readily available indoor plants commonly used in commercial UK offices or domestic homes, based on data from Ambius, a leading, commercial interior landscaping company and the Royal Horticultural Society (RHS) retail sales (personal communication). The plants represented examples of a range of physical characteristics and metabolic pathways (Table 7.1); the plants were evergreen, with no flowers, no excessively large specimen plants, and were of a comparable green colour. As the focus of the research was on understanding the influence of plant shape, strong variegation and markings were avoided except for *Sansevieria* and *Calathea* which had patterns on the leaves, but the contrast of these was reduced using Adobe Photoshop CS (Adobe Photoshop CS., 2004). Different plant shapes were included that are typically used in plant landscaping and were representative of different theories about the impact of plants on SWB (Smith, 2011; Muderrisoglu et al., 2009; V. Lohr & Pearson-Mims, 2006). To enable direct comparison of the effect of plant shape, and control other variables of plant appearance, *Ficus benjamina* plants of the same size and from the same batch were pruned into the shapes Sphere, Column, Pyramid and Spreading. The plants were photographed in the same type of pot, against the same background and adjusted using photo-editor to make the images comparable size, colour and brightness.

Image No.	Plant	Shape	Leaf and canopy properties
1	*Ficus benjamina* 'Danielle'	Column soft	Small, slender, glossy, green, soft pointed leaves. Graceful medium dense canopy. Woody plant. C3 metabolism
2	*Sansevieria trifasciata laurentii*	Column sharp	Long, upright, thick, broad sword shaped leaves. Crassulacean Acid metabolism (CAM)
3	*Echinocactus grusonii* (Cactus*)	Sphere small spikey	Succulent. Glossy green ribs with radial yellow spines, not leaves. CAM
4	*Ficus benjamina* 'Danielle'	Sphere – Large soft	See plant 1. Thick, lush, dense glossy canopy
5	*Ficus benjamina* 'Danielle'	Pyramid - neat	See plant 4
6	*Dypsis lutescens* (neglected palm**)	Spreading	Unhealthy plant. Tropical. Long arching, linear, narrow pointed leaves. Graceful shape. C3 metabolism
7	*Dypsis lutescens* (Palm*)	Spreading	Healthy version of plant 6
8	*Ficus benjamina* 'Danielle'	Spreading - Savannah like	See plant 4 but less dense canopy
9	*Calathea* 'White star'	Spreading	Green and white striped effect, individual broad leaves on arching stems. Statement plant. C3 metabolism
10	*Asplenium nidus*	Spreading	Broad, large lance shaped fronds with wavy edges. Fern. C3 metabolism
11	*Epipremnum aureum*	Pyramid - natural	Large, glossy, rich green and yellow, heart-shaped leaves. C3 metabolism
12	*Dracaena marginata*	Sphere -large spikey	Slender, narrow pointed leaves. Which form at the top of upright stems. Sparse canopy. C3 metabolism

Table 7.1: **Characteristics of the plants included in the survey.**

*For simplicity, the common names of palm and cactus are used in this study

** Hereafter referred to as neglected palm

The plants represented a range of impacts on IAQ and RH determined from experimental data (Chapters 3 and 5) and previous research (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014). The plants were all healthy except for one plant (Fig. 7.1, plant 6), which was included to determine if unhealthy plants affected participant's responses, in particular the impact on perceived SWB. Plant 6 was an unhealthy version of Plant 7.

Figure 7.1: Selection of plants used in the survey. Refer to Table 7.1 for key and explanation

7.2.3 Statistical analysis

A sensitivity test was conducted using G*Power 3.1 software (Faul et al., 2009), this revealed that a repeated measures, within subjects MANOVA, with 520 participants, across 12 conditions, would be sensitive to effects of Cohens f = 0.05 (η_p^2=0.002), with 80% power (alpha = 0.05). This means the study should be able to detect small effects according to Cohens criteria (Cohen, 1998), and compared to examples in the literature (Lee et al., 2014). All other statistical analyses were carried out using SPSS version 25 (IBM).The frequency of participants' (N=520) first and last choice preference votes was determined for each plant and tested to determine whether there were differences in plant preference by means of a chi- squared test.

Differences between participants' ratings of the descriptors were tested using a mixed design ANOVA. Mauchly's test was conducted to test the assumption of sphericity and adjusted data are reported. Post hoc, Scheffé multiple pairwise comparison tests were used to further test for significant differences between plants for each descriptor (Ho, 2006; Summit & Sommer, 1999). Bonferroni adjustment was included to account for inflated Type 1 error due to multiple comparisons.

The correlation between the mean scores for the predictors (Beauty, Interesting, Soft, Relaxing and Depressing), and participants perception of the impact of the plant on SWB, IAQ and RH were assessed using Pearson correlation coefficients, and multiple linear regression analysis was conducted to determine if the perceived benefit of the plant for SWB, IAQ or RH (outcome variable) could be predicted from the mean scores for the descriptions of the appearance (the predictors).

Data was verified to ensure that it met the assumptions of linearity, homoscedasticity independence of error term normality of the error distribution and multicollinearity. Initially the individual predictor variables (Beautiful, Interesting, Soft, Healthy, Relaxing and Depressing) were entered into the regression analysis all at once and the outcome variable was set as SWB, the analysis was repeated for the outcome variable as IAQ and RH. The importance of each variable was then assessed through a hierarchical multiple regression where the variables were entered in the order of importance identified from the correlation analysis.

The rank totals for the plant characteristics (colour, shape, leaf shape, leaf pattern, texture) were assessed using the Friedman's ANOVA statistical test, and Wilcoxon signed-rank tests were conducted on each pair of plant characteristics to determine the order of importance (all significance levels minimum of 0.05). These tests are appropriate for non-parametric data.

7.3 Results

7.3.1 The participants

Responses were received over a four-week period during May-June 2021, and 520 participants who successfully completed all sections of the questionnaire were included in the analysis. The majority (69%) of participants were female, 29% were male and 2% did not specify. The participants included a balance of age groups although the majority, 63%, were under 50 years old and further 35% were 50-65 (Table 7.2).

Summary of participants’ gender and age							
	Under 25	**25-34**	**35-49**	**50-64**	**65+**	**Not specified**	**Total**
Female	16	103	114	116	9	2	360
Male	5	36	48	53	3	3	148
Not specified			3	1		8	12
Total	21 (4%)	139 (27%)	165 (32%)	170 (33%)	12 (2%)	13(3%)	520

Table 7.2: Numbers of participants in various age and gender groups, with % of the total provided in brackets.

The majority (67%) of the participants were employed; 29% worked in professional roles, 17% in teaching roles, 17% were students, 11% were in administrative roles, 15% were in other roles and 6% were retired. Due to the pandemic lockdown restrictions at the time of surveying, 74% of participants spent the majority of their day at home, 10% spent their working day in an office building and 10% worked indoors but not in an office. Participants were asked if they had a background in: Environment (29%), Construction (16%), Art (8%), or None of these (48%) (data not shown).

The survey was voluntary with no incentives. The majority (96%) of participants stated that they liked indoor plants and enjoyed them both at home and work (84%). 79% of participants enjoyed looking after indoor plants either at home or at work, but 25% did not like looking after plants at work. 8% of participants had become interested in indoor plants during lockdown. The majority of participants had views of nature/plants during the day: 58% responded “A lot”, 33% said “A little” and 9% responded “None” (data not shown).

7.3.2 Plant preference

The results of the Chi-squared test showed significant differences between the rated preferences of the plants, $\chi^2(df=11) = 277.62$, $p < 0.001$. *Epipremnum, Ficus* sphere, Palm *and Ficus* column were significantly preferred to all other plants, receiving 113, 90, 71 and 63, first choice votes respectively from a possible total of 520 but there was no significant difference between these top four plants.

The neglected palm was significantly the least preferred plant with 60% (N=313) of the participants voting it last (Figure 7.2).

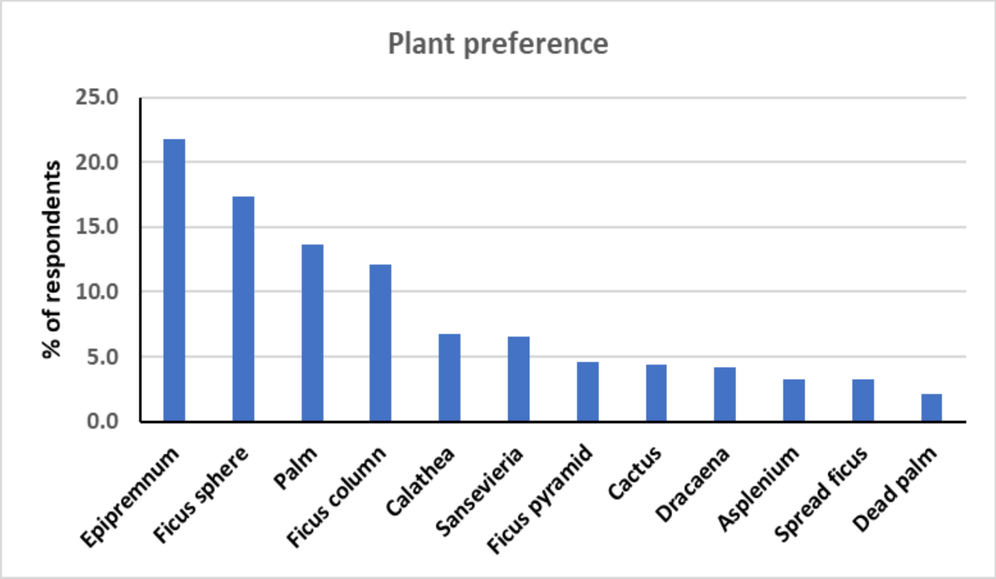


Figure 7.2: The preferred order of plants based on the percentage of participants (N=520) stating their first choice of plant

There was a significant effect of participants background on plant preference, X^2 (df=44) = 66.27, $p < 0.05$. More participants with a background in Construction (30%) and Art (33%) preferred the *Epipremnum* plant, compared to people without these backgrounds (19%) who preferred both *Ficus* Sphere and *Epipremnum* (Figure. 7.3).

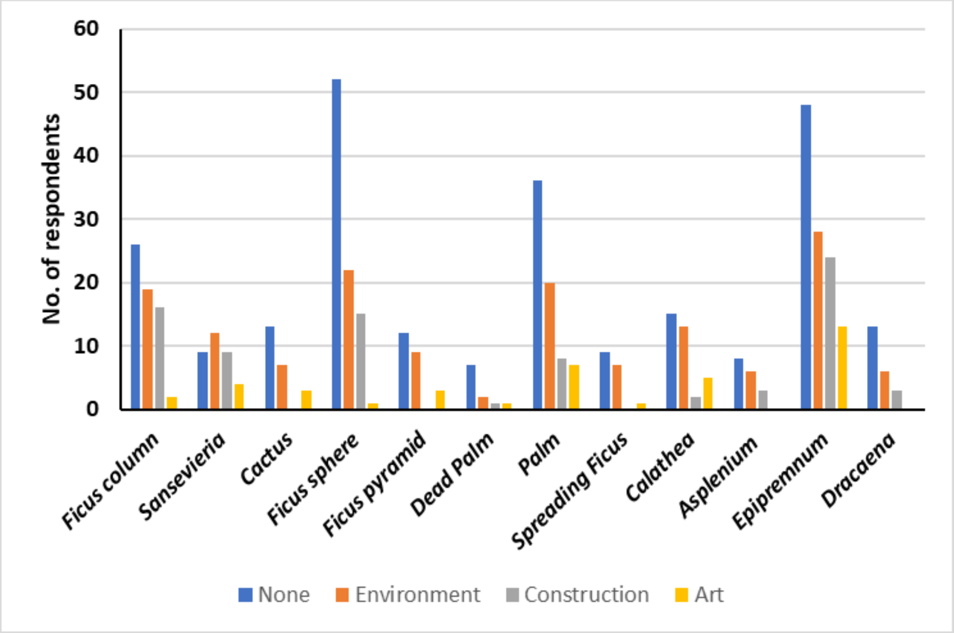


Figure 7.3: Effect of participants' background on their preferred plant choices. "None" refers to participants with no background in environment, construction or art

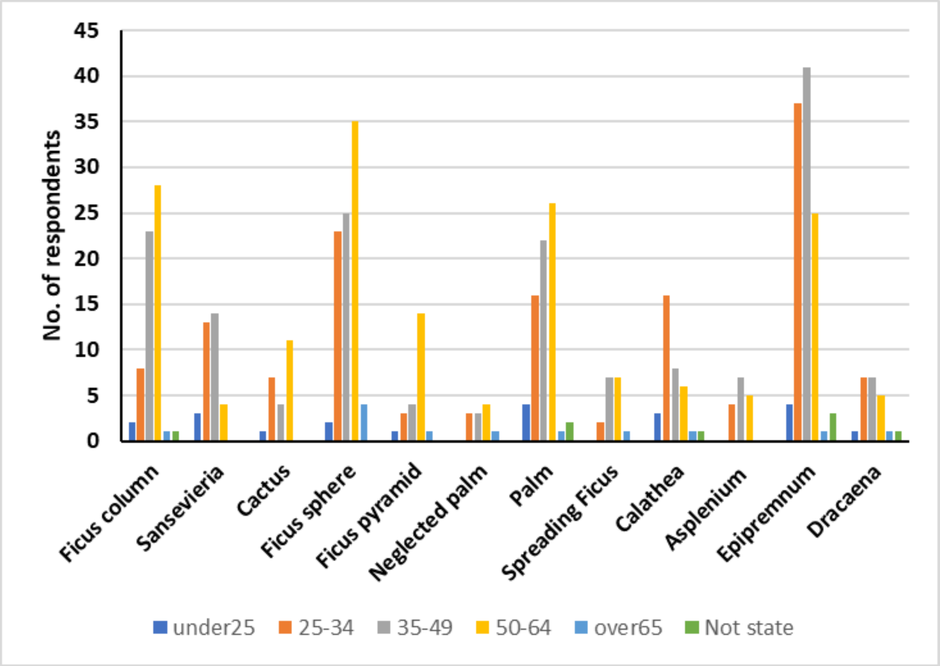


Figure 7.4: Preferred plant choices for different participant age groups

There was a significant effect of respondents' age on plant preference, X^2 (df=5) = 371.54, p<0.001 (Figure 7.4) but further inspection, revealed this difference was only between the 25-34 year olds (N=139), who preferred *Epipremnum* and the 50-65 year olds (N=170), who preferred the *Ficus* sphere plant, F(5, 509) = 2.66, p<0.05. (Fig.7.6).

There were no significant effects of gender X^2 (df=33) = 41.99, p =0.14, occupation, X^2 (df=88) = 92.21, p =0.36 or views of nature from their buildings, X^2 (df=22) = 18.80, p =0.66, on the participants plant preference.

7.3.2.1 Plant shape and preference

Within the *Ficus* plants, the most preferred shapes based on total of first choice votes, were the sphere (46%), column (33%), pyramid (12%) and spreading (9%). However, as the plants were ranked within a larger group of plants and not solely against each other this result cannot be statistically validated.

7.3.3 Descriptive scores

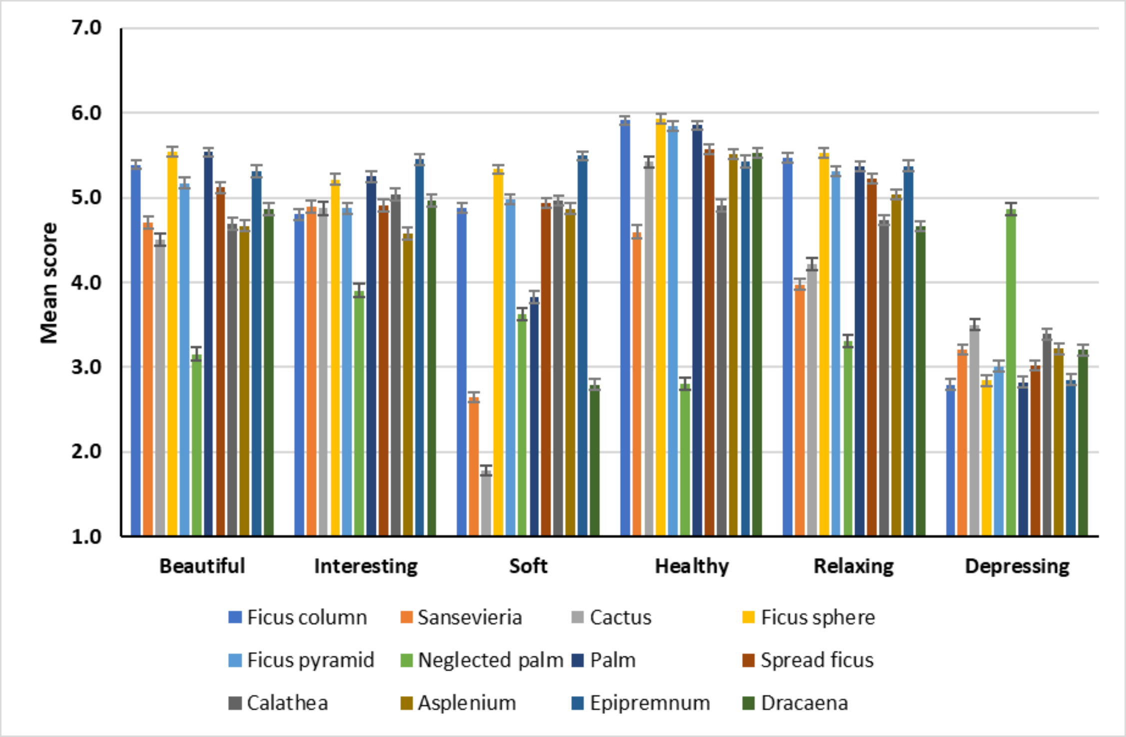


Figure 7.5: Effect of the plant type on the descriptive scores; bars represent the mean scores (N=520) ± SEM, on a 1-7 scale. Full table of scores included in Appendix 2.

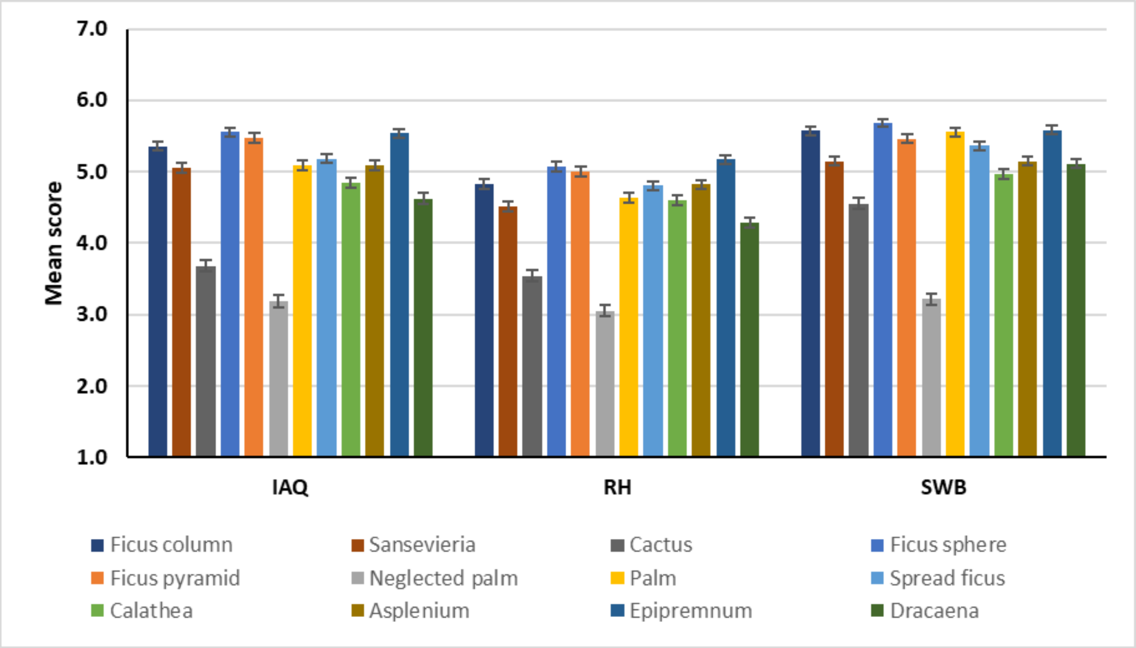


Figure 7.6: Effect of the plant type on the scores for perceived benefit for IAQ, RH and SWB; bars represent the mean scores (N=520) ± SEM on a 1-7 scale.

Results of the mixed method multivariate analysis of variance (MANOVA) showed the plant type had a significant effect on the mean scores for the descriptive terms F(11, 254) = 14.1, $p<0.001$. Further detailed analysis, using separate repeated measure ANOVAs, revealed there were significant differences between the plants for each of the individual descriptive scores (F-statistics shown in in Table 7.3), (all p's<0.001). As all tests violated Mauchly's sphericity test, the Huynh-Feldt procedure was used to correct for possible inflations of the type 1 error rate by modifying the degrees of freedom (Huynh & Feldt, 1976).

Repeated measures ANOVA	
	F statistic
Beautiful	(8.8, 4087.75) = 129.08
Interesting	(8.94, 4335.92) = 41.98
Soft	(7.76, 3598.68) = 417.44
Healthy	(7.82, 3800.87) = 234.25
Relaxing	(8.89, 4186.05) = 152.60
Depressing	(9.04, 4336.92) = 107.26
IAQ	(6.21, 3006.19) = 282.33
RH	(6.53, 3158.01) = 192.16
SWB	(7.65, 3734.23) = 201.00

Table 7.3: Results of the Repeated measures ANOVA for the mean scores for each descriptor and outcome variable assessed on the bipolar scales.

There was no significant effect of the participants' demographics on the descriptive scores; gender, F(2,399)=.182, $p>0.5$ η^2=.001, age, F(5,399)=1.83 $p>0.1$, η^2=.022, occupation F(8,399)=1.356, $p>.1$, η^2=.026, The effect of participants' background and other minor effects are discussed below.

The data for all descriptive scores discussed below are provided in Figure 7.5.

7.3.3.1 Ugly-Beautiful scores

All plants except the neglected palm, were considered beautiful to some extent although the perception of beauty varied between participants. *Ficus* sphere, palm, *Ficus* column and *Epipremnum* achieved the highest mean scores for beauty (Fig. 5) but there was no significant difference between these top four plants. The opinions about the beauty of the Cactus plant were most divided between the participants. The neglected palm scored significantly lower, ($p< 0.05$) than all other plants with a means score on the ugly side of the scale, thus the healthiness of the plant appears to increase the perception of its beauty. Between the four *Ficus* shapes, the sphere and column shapes were rated significantly more attractive than the pyramid and spreading shapes, ($p<0.05$). Common physical characteristics associated with the more beautiful plants were rounded leaves and softer canopy edges. Comments from participants suggest that the sharp spikes on the cactus, snake like appearance of *Sansevieria* and the leaf pattern and colour of *Calathea* affected the beauty of these plants.

7.3.3.2 Boring - Interesting scores

The *Epipremnum* plant which had leaves on trailing vines, was reported as significantly more interesting than all other plants except palm ($p< 0.05$). There was no significant difference between the mean scores for Palm*,* *Ficus* sphere, *Calathea* and *Dracaena* but these four were significantly more interesting than the remaining seven plants ($p< 0.05$). The neglected palm was rated as the most boring plant ($p< 0.05$). Between the four *Ficus* plant shapes, the Sphere was significantly more Interesting than all other shapes ($p<0.05$) but when comparing the different shapes across all species, no single canopy shape determines how interesting a plant will appear.

7.3.3.3 Sharp - Soft scores

Ficus sphere and *Epipremnum* had the softest appearance ($p<0.05$), whilst cactus*, Sansevieria* and *Dracaena* were considered significantly sharper than all other plants ($p<0.05$). The mean scores for the different *Ficus* shapes showed the sphere had a significantly softer appearance, but there was no difference between the remaining three shapes ($p>0.05$). Plants with a sharp appearance typically had narrow pointed leaves on a sparse canopy or prickly spikes, suggesting that participants associated the contours of the canopy with the sharpness or softness of the plant rather than the geometrical canopy shape.

7.3.3.4 Unhealthy – Healthy scores

All plants except for the neglected palm were considered to have a healthy appearance but the palm, *Ficus* column, *Ficus* sphere and *Ficus* pyramid achieved significantly higher scores compared to all other plants ($p<0.05$). The neglected palm achieved the lowest score for healthiness ($p<0.05$) followed by *Sansevieria* and *Calathea.* Between the four differently- shaped *Ficus* plants, the spreading *Ficus*, was reported as significantly least healthy, ($p<0.05$) but there were no other significant impacts of canopy shape on Healthy scores. Overall, participants viewed the healthiness of the plant separately to canopy shape or softness and typical characteristics of healthy plants were bright green colour and a dense canopy.

7.3.3.5 Stressful - Relaxing scores

Ficus sphere, *Ficus* column, palm, *Epipremnum* and *Ficus* pyramid, had the most relaxing appearance and highest mean scores but there was no significant difference (p>0.05) between these five plants. The neglected palm was significantly more stressful than all other plants followed by cactus, *Sansevieria, Dracaena* and *Calathea. S*ome participants found the markings on the leaves of *Sansevieria* and *Calathea* stressful as they associated them with snakes, dangerous insects or animals.

Comparison of the four *Ficus* shapes showed, sphere and column were significantly more relaxing than pyramid and spreading shapes. When the same shapes in different species were compared, such as the soft *Ficus* column and the sharp *Sansevieria* column or the soft *Ficus* sphere against the spikey sphere of cactus and Dracaena, it is apparent that sharp edged leaves and spikes reduce the relaxing appearance of the plant.

7.3.3.6 Uplifting - Depressing scores

This question was reverse scored, so the lower the score the more uplifting the plant appearance. All plants, except the neglected palm, had an uplifting appearance. The four most preferred plants; *Ficus* column, *Ficus* sphere, palm and *Epipremnum* achieved the highest mean scores (p<0.05) for Uplifting, although there was no significant difference between these four (p>0.05). The neglected palm had significantly the most depressing appearance (p<0.05).

Between the *Ficus* plants of different shapes, there was no significant difference between column or sphere, but the column was more uplifting than pyramid and spreading. Plants with prickles, sharp edged leaves and striped patterns were associated with a less uplifting appearance.

7.3.3.7 Perceived benefit for SWB

Most participants perceived that all plants tested, except the neglected palm*,* would benefit their SWB as the mean scores were all higher than the mid-point of the scale (Figure 7.6). The most preferred plants in the preference ranking, *Ficus* sphere *Ficus* column, palm, *Epipremnum*, and *Ficus* pyramid achieved significantly higher scores than all other plants (p<0.05) but there was no significant difference between them. The neglected palm scored significantly lower than all other plants. Comparing the scores for the healthy and neglected palms revealed that unhealthy plants have a low or negative impact on participants' perceived SWB. Within the differently shaped *Ficus* plants, participants perceived that the sphere, column and pyramid shapes would have a higher benefit for their SWB than the spreading *Ficus* shape.

7.3.3.8 Perceived benefit for IAQ

The mean IAQ scores for all plants except for the neglected palm and cactus, were above the mid-point of the bipolar scale, showing that participants perceived the majority of the plants in this survey would have a positive impact on IAQ. *Ficus* sphere, *Epipremnum, Ficus* pyramid and *Ficus* column had the highest mean scores and perceived benefit for IAQ (scores approximately one standard deviation (SD), higher than the group mean). There was no significant difference between the top three, but the scores for all four plants were significantly higher than all other plants.

The plants with a perceived mid-range benefit (scores less than half one SD higher than the group mean) for IAQ, were Spreading *Ficus*, *Palm*, *Asplenium*, and *Sansevieria*. The *Palm* plant, which was one of the most preferred plants in the preference test and attained high scores for most other attributes is perceived as having only a medium benefit for air quality. *Calathea* and *Dracaena* with scores up to half a SD lower than the group mean, were perceived as having a positive, but lower benefit for IAQ compared to the other plants.

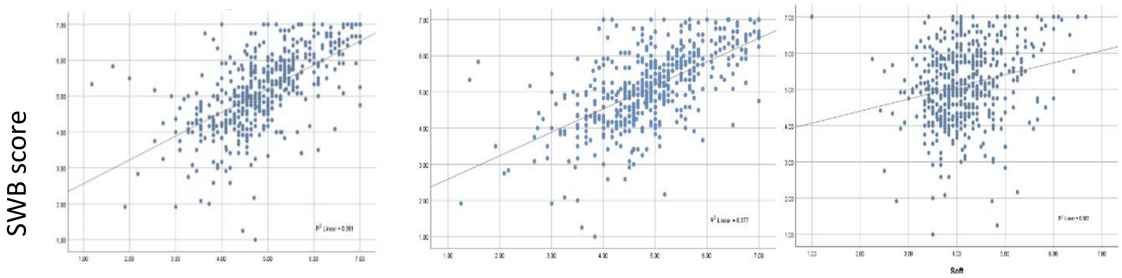
The neglected palm was perceived to have the lowest benefit for air quality, followed by the cactus. Comparison of the four differently shaped *Ficus* plants showed the sphere and pyramid had significantly higher scores than the column and spreading shapes. The column was significantly higher than the spreading shape ($p<0.05$).

7.3.3.9 Perceived benefit for RH

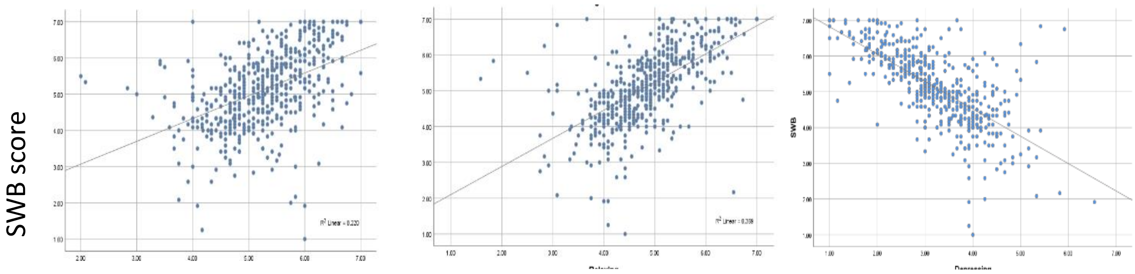
All plants were perceived as having a lower benefit for RH compared to IAQ although the participants scored the impact of individual plants differently than for IAQ. *Epipremnum* and *Ficus* sphere, were perceived to have the greatest benefit for RH. Their mean scores were over one SD higher than the group mean and were significantly higher than all other plants tested ($p<0.05$). *Ficus* pyramid achieved the next highest mean score which was significantly higher than the remaining plants ($p<0.05$). Plants with a perceived mid-range benefit for RH, with means up to half a SD above the group mean, were *Ficus* column, spreading *Ficus*, *Asplenium*, palm and *Calathea*. The mean score for *Sansevieria* was 10% lower than the group mean and therefore perceived to have a lower benefit for RH. *Dracaena*, cactus, and the neglected palm had significantly the lowest perceived benefit for RH ($p<0.05$).

7.3.4 Correlation between plant appearance, SWB, IAQ and RH

Scatter plots and Pearson correlation tests revealed a significant positive correlation between the perceived benefit for SWB, IAQ, RH, and all descriptors of the plant appearance, except for a significant negative correlation with Depressing (Figs. 7.7 and 7.8) (data for RH not shown).



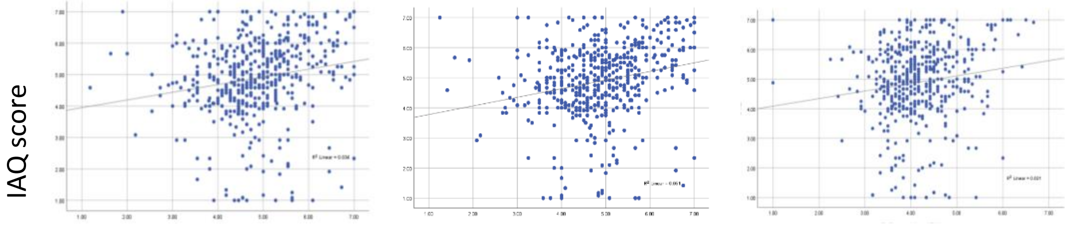
Beauty score (r=.60**) Interesting score (r= .61**) Soft score (r= .23**)



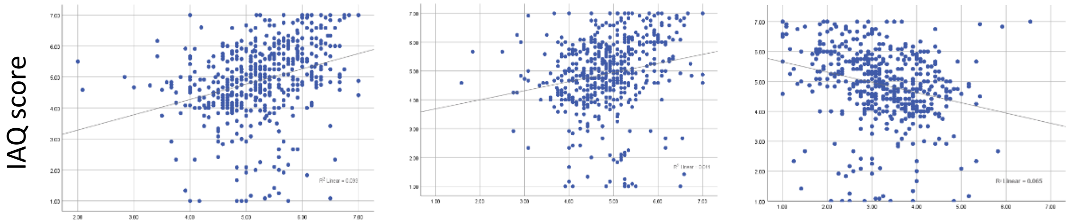
Healthy score (r= .47**) Relaxing score (r= .61**) Depressing score (r= -.69**)

Figure 7.7: Correlations between mean scores for descriptors and perceived SWB benefit (N = 520). Showing Pearson's r coefficient (significant p<0.01) and lines of best fit.**

The order of strength of correlations for the descriptors for SWB was Depressing, Interesting Relaxing, Beautiful, Healthy and Soft and for IAQ; Healthy, Depressing, Interesting, Relaxing, Soft and Beautiful. For RH the correlations were in the same order of strength as for IAQ, but the associations were weaker. For RH the highest correlations were for Healthy (r= .21), Depressing (r= -.18) and Interesting (r= .15). The order of strength of the correlations were used as the order of importance in the hierarchical method of entry of regression (section 7.3.5).



Beauty score (r = .18**) Interesting score (r = .23**) Soft score (r = .15**)



Healthy score (r = .31**) Relaxing score (r = .20**) Depressing score (r =- 26**)

Figure 7.8: Correlations between means scores for descriptors and perceived IAQ benefit (N=520). Showing Pearson's r coefficient (significant p<0.01) and lines of best fit.**

7.3.5 Predicting the benefits for SWB and IAQ from the plant appearance

Multiple linear regressions were conducted using the scores for the descriptive terms as predictor variables and setting the outcome variable separately as either SWB, IAQ or RH.

7.3.5.1 Multiple linear regressions of SWB and predictor variables

A significant relationship between the descriptive terms and the score for SWB was revealed when all the predictor scores were into the regression model at once. The predictors accounted for a significant proportion of the variation in SWB scores with the model summary R^2=0.52, F(6,511) = 92.187, $p<0.001$. The standardized regression coefficients (b), showed that when all the predictors are entered into the model, only Depressing (b= -0.422, t=-8.785, $p<0.001$), Interesting (b= 0.160, t=-2.606, $p<0.01$) and Relaxing (b=0 .137, t=2.468, $p<0.05$) were significant predictors of SWB scores. The further addition of predictors Beautiful, Healthy and Soft were not significant. The values for Depressing have a negative value, showing that as the score for Depressing appearance increases, the score for SWB decreases.

Running the model with the hierarchical entry method revealed that Uplifting-Depressing mean scores alone accounted for a significant proportion (47.1%) of the variation in SWB scores with a model summary of $R^2=0.471$, $F(1,516)=460.061$, $p<0.001$. The addition of the Interesting mean scores, accounted for a further 3.6% of the variation in SWB scores (R^2change=0.036, F change(1,515)= 37.103, $p<0.001$) and the addition of Relaxing accounted for a further 1% of variation in the SWB score. (R^2 change =0.01, F change (1,514) = 10.122, $p=0.002$). The further addition of other predictors was not significant ($p>0.05$).

Prediction Equation for SWB **(7.1)**

Predicted SWB mean score = 4.586 + (-0.470 x Depressing) + (0.169 x Interesting) + (0.177 x Relaxing)

The methods of entry above showed the Depressing predictor accounted for a significant proportion of the variation in the SWB score. It is possible that some of the variation in SWB score, that could be shared and predicted by the other predictors (Soft /Healthy /Beauty /Relaxing /Interesting), would be ascribed only to Depressing as this was entered into the analysis first. To ensure the effects of Depressing were not concealing the effects of other predictors, the regression model was run with the predictors entered in reverse order: Soft, Healthy, Beauty, Relaxing, Interesting, Depressing. When Soft was entered on its own, it accounted for 6% of the variation in SWB scores, $R^2=0.062$, $F(1,516)= 33.93$, $p<0.001$, when Healthy was added to the model, this accounted for a further 17.1% of the variation with an R^2 change =0.171, F change(1,515)= 115.07, $p<0.001$ and Beautiful accounted for 14.8% of the variation, R^2 change =0.148, F change(1,514) = 123.32, $p<0.001$.

The comparison of the methods showed that each of the predictors can predict some of the variance of the SWB score, but their contribution reduces and can become insignificant as the stronger predictors are added to the model.

7.3.5.2 Multiple linear regressions of IAQ and predictor variables

Regression analysis revealed a significant association between the descriptive terms and the outcome variable IAQ. The predictors accounted for approximately 12% of the variation in IAQ, with the model summary of: $R^2=0.119$, $F(6,510)=11.51$, $p<0.001$. The standardized regression coefficients showed that only Healthy ($b= 0.286$, $t=-5.041$, $p<0.001$) and Depressing ($b=-0.173$, $t=-2.658$, $p<0.01$), were significant predictors of IAQ scores. The analysis revealed the prediction equation 7.2.

Prediction equation for IAQ (7.2)

Predicted IAQ mean score = 3.787 + (0.462 x Healthy) + (-0.232 x Depressing)

Results of the hierarchical regression analysis revealed that Healthy mean scores alone accounted for 9.8% of the variation in IAQ scores with $R^2=0.098$, F(1,515)=55.64, $p<0.001$. The addition to the model of the Depressing mean scores, accounted for a further 0.9% of the variation with an R^2 change=0.009, F change(1,514)= 5.163, $p<0.001$. The addition of further predictors accounted for less than 1% each.

7.3.5.3 Multiple linear regression of RH and predictor variables

Entering all predictors into the regression model at once with RH as the outcome variable, revealed a significant association. The predictors accounted for approximately 6% of the variation in RH score, with the model summary of: $R^2=0.062$, F(6,509)= 5.57, $p<0.001$. The standardized regression coefficients, showed that only Healthy (b= 0.209, t= 3.548, $p<0.001$) and Depressing (b=-0.133, t =-1.982, p=0.048), were significant predictors of RH score. Entering the predictors in a hierarchical model showed Healthy accounted for 4.8% of the variation in RH score with, $R^2=0.048$, F(1,514)=26.236 $p<0.001$. The addition of further predictors accounted for less than 0.5% of variation and were not significant ($p>0.05$). The results are comparable with those for IAQ but the strength of associations between the predictors and the outcome variable of RH is weaker.

7.3.6 Analysis of ranked data for plant characteristics

	No. of respondents ranking				
	Plant shape	**Colour**	**Leaf shape**	**Leaf pattern**	**Texture**
1st	276	163	46	19	17
2nd	120	159	127	66	48
3rd	70	95	184	111	59
4th	33	57	114	164	152
5th	21	46	49	160	244

Table 7.4: Results of the plant characteristic ranking test, showing the frequency of response and the rank position for the five physical characteristics in order of importance for the attractiveness of indoor plants. Data are the results from 520 participants.

The participants identified a significant difference in the importance of the plant characteristics on the attractiveness of indoor plants, as the Friedman χ^2 statistic was significant, $\chi^2(df=4) = 712.25$, $p < 0.001$ and Wilcoxon signed-rank tests (all p's<0.05), confirmed that the order of importance, first to last, for the five characteristics was: Plant shape, Colour, Leaf shape, Leaf pattern and Texture.

7.3.7 Thematic analysis of participants' comments

Participants showed good engagement with the survey and 39% provided additional comments (203 participants recorded 262 comments). The frequency of comments recorded for each theme is outlined in Table 7.5.

Theme	Sub theme	Examples of comments
Aesthetic appearance (85)	Interest (25)	Decoration and interest Add interest to room/office. Easy to change. Needs to be interesting to look at - not necessarily beautiful. Size and shape most important. I like trees - plants remind me of them Flowering plants add more interest. Trailing plants more interesting. Rounded leaves better. I like statement plants or rare ones as talking point Leaf movement, catching insects, smell; all interesting
	Colour (19)	Add colour. Green colour is pleasing. I would like more colour. Like bright luscious fresh colours Like some contrast in colour not just solid green.
	Size (9)	I like: big and bold / vibrant and interesting / colour and variety. Plant size important - both big and small. Has to fit space. Often bigger preferred at work- smaller at home. Choice depends on space available.
	Arrangements (13)	Variety and shapes in planting arrangements important. Look better in groups.
	Flowering (14)	Like flowering plants - add interest and colour
	Interior decoration (5)	The planters or pots can add interest. Soften & calms the space. Can act as screen in office. Provide privacy on desk. LED lights look good on them.
Well-being (71)	Happiness (50)	Plants bring happiness and joy. "I love them. I have 160 at home". Plants are uplifting. Welcoming.
	Calming (8)	Relaxing /calming. Mindfulness.
	Health (7)	Bring a healthy feel to the environment. Benefit health.
	Nurturing (3)	The effects mainly due to the appearance but can be act of nurturing them.
	Nature indoors (2)	I like having living things in my home. Brings outdoor inside.
	Social benefit (1)	Can help team building – e.g. chilli growing in office.

Plant maintenance (51)	Maintenance (43)	Low maintenance is requirement. Ease of maintenance important - often dictates plant choice - need to be easy to look after. Watering them can be a chore. Light requirement affects choice e.g. in office. Cactus - liked because low maintenance
	Stressful (9)	Looking after them & risk of them getting sick - fear of killing them is stressful (especially presents). Sad when they die. *Calathea* and *Palm* are stressful and they die. Not knowing how often to water is a worry. Shedding leaves or making mess is undesirable.
Plant health (22)	Healthy plants - positive (8)	Healthiness of the plant is important. Healthy plants have lots of lush, bright green leaves Bushy plants are better than spindly ones.
	Unhealthy plants - negative (14)	Dead, sick looking ones are depressing and worse than none at all. Variegated plants look unhealthy.
Adverse effects (11)	Bugs & pests (2) Toxins (2)	Bugs, toxicity, allergy, pollen, risk to pets all causes of concern and affect choice.
	Pets (5)	Risk or danger to pets
	Dust (2)	Plants attract unwanted dust.
Memories (4)	Happy (3)	Memories attached to plant can affect like/dislike– “My first plant”, “My Mum had one of those”, “Palm reminds me of tropical holidays”,
	Negative (1)	“Bad experience with cactus prickles”
Air quality (6)	Benefit IAQ	AQ impact – e.g. “they remove toxins” “remove CO_2” “they improve the air”, “improve office climate”
Danger (6)	Spikes (4)	Sharp points/spiked leaves can be dangerous. Cactus spikes dangerous. *Dracaena* – points could catch your eyes.
	Leaf markings (2)	Stripey markings on leaves can evoke fear or dislike - *Sansevieria* associated with snakes -not nice. *Calathea* stripes evoke both like and dislike.
Natural (4)	Natural	Naturalness of plant appearance important –e.g. should not look manicured. Adds natural feel.
Cost (2)	Cost	Cost is important and affects my choice.

Table 7.5: Summary of the thematic comments recorded in the survey, open text, section The number in brackets (N) is the frequency with which the comment was recorded.

The appearance of the plant and the aesthetic contribution received the most comments (85). Respondents revealed that plants are decorative, but they are more than just objects of beauty; they also add interest and colour. Statements also suggested that grouping of different shapes and colours of plants in arrangements are important to add more interest and the planters or pots can add to the decoration. Plants were also identified as being useful screens in the office and on desks to provide sound barriers and privacy.

The benefit of plants for well-being or happiness was the next most frequent theme (71 comments). Participants used words such as welcoming, joyful, happy, relaxing and calming. These uplifting effects were mainly due to the plant appearance and the act of viewing it, but plants are also living things and some participants found it rewarding to nurture, care for and watch them grow. Three people commented that plants make the environment feel healthier which makes people feel well. One respondent commented that growing a shared chilli plant in the office had been great for team bonding and bringing people together.

The maintenance of plants was important and is a significant factor affecting plant purchases, with most people wanting easy to maintain plants. Only one person specifically referred to the plant light requirement affecting their choice. There were also 32 comments about the stress of caring for plants such as the hassle of watering plants, or feeling stressed if the plants became sick, were covered in pests, or died.

Plant health was important: healthy plants were described as appearing lush, bushy, with lots of bright green, luscious leaves. Unhealthy plants were regarded as spindly, depressing, and worse than having no plants at all. One respondent commented that variegated plants look less healthy. There were also four comments about liking plants to appear natural as a reminder of nature and therefore not wanting the plant to be too manicured. Under the theme of Adverse Effects, concerns about pests, toxins, pollen, allergies, danger to pets and dust collection were cited. Cost was not mentioned in the survey and there were only two comments about the cost affecting choice although other surveys have identified this as a key factor affecting people's purchases(Hall et al., 2019).

7.4 Discussion

7.4.1 The effect of plant appearance on people's preferences and perceptions

The results of the bipolar scores and preference test showed the physical appearance of the plant had a significant impact on participant's emotional response and aesthetic preference. All healthy plants tested were considered beautiful to some extent and there was a significant relationship between the physical appearance of the plant and its perceived impact on SWB, IAQ and RH.

There were individual differences in plant preference and opinions of beauty between participants but overall, participants perceived that the most preferred plants, *Epipremnum, Ficus* sphere, palm *and Ficus* column, would have the highest benefit for their SWB and this would increase with increasing plant attractiveness. Previous research has also shown that exposure to more beautiful plants increased prosocial behaviour (Zhang et al., 2014). The least preferred, neglected palm plant, was perceived to have the lowest benefit for SWB.

Although there is little data on responses to the appearance of indoor plants, our findings paralleled results from studies of outdoor plants and trees, where a high correlation was found between participants' emotional responses, preferences and well-being (V. Lohr & Pearson-Mims, 2006; Purcell, Peron, & Berto, 2001). For example, Lohr & Pearson-Mims (2006), measured the aesthetic preferences, affective responses, skin temperature and blood pressure of participants whilst they viewed photographs of individual trees of different shapes. Participants reported feeling happier and their diastolic blood pressure was lower when they viewed images of their most preferred tree shape and they appeared to respond more positively to trees with denser canopies. People also responded very positively to other tree shapes, and the authors concluded that human well-being can be improved by planting trees of any form. In addition a survey of office workers preferences for images of living roofs (Lee et al., 2014), showed that the plant characteristics influenced their preferences, the most preferred vegetation had the greatest restorative effect and there was a high value for healthy landscapes and green foliage (Lee et al., 2014). In our study participants perceived that viewing most indoor plants would benefit their well-being.

Regression analysis revealed the terms, Uplifting, Interesting, Relaxing and Beautiful were the most significant predictors of the perceived benefit of the plant for SWB. The benefit for SWB was not just related to the beauty of the plant but also the interest that the plant appearance holds for the participant.

Numerous studies reporting the restorative effect of indoor plants have attributed their findings to the Attention Restoration Theory (ART) (Shibata & Suzuki, 2001; Lohr, Pearsons-Mims, & Goodwin, 1996). One of the key elements of ART is *fascination* whereby the stimulus has to be sufficiently interesting to attract people but not overly complex such that too much directed attention would be required (Berto et al., 2010; Berto, 2005). The impact on mental fatigue was not measured in this study so there is no clear evidence that the perceived benefit for SWB is due to ART, but the results do provide some evidence that the interest or fascination of the plant influences the perceived benefit for SWB. By contrast, studies by Evensen et al. (2015), found that interiors where indoor plants were present were rated as more fascinating than those without plants or with inanimate objects, but this did not lead to greater restorative effects.

A study by Haga et al. (2016), showed that the restoration from nature experiences was not due entirely to responses shaped by evolution but also depended on the meanings associated with the stimulus. The qualitative feedback in this study provides evidence to support this, for example participants stated that memories attached to certain plants affected their responses (e.g. the palm was associated with holidays and happy memories).

The neglected palm plant was perceived to have a very low impact on participants' SWB. It was the least attractive, least preferred plant and participants thought the appearance was unhealthy and depressing. This important finding shows that to benefit occupants' well-being, sick or dead plants should be removed from the indoor environment. However, we investigated the responses to one unhealthy plant, but a broad spectrum of plant healthiness exists which could affect the plant appearance and people's responses. Furthermore, plant maintenance was identified as a main concern in participants' comments. This might affect plant health and hence people's subsequent responses to the plant in real settings. Guidance on plant choice and care at the point of sale or the use of professional maintenance companies could help alleviate some of these concerns.

The response of participants to plant colour was not tested here but several studies have reported that the green colour in plants is preferred as it has a calming, relaxing, uplifting effect (Jang et al., 2014; Elsadek et al., 2013; Kaufman & Lohr, 2004) whereas brown is strongly disliked and has been associated with declining trees (Muderrisoglu et al., 2009; Kaufman & Lohr, 2004). The brown colour could therefore help to explain participants dislike for the neglected palm and its perceived negative effect on their SWB.

The appearance of the plant had a significant effect on the perceived benefit of the plant for IAQ and RH although the perceived benefits for IAQ were lower than for SWB and the plants which participants perceived would have the greatest impact on IAQ, were different to those for SWB. *Ficus* sphere, *Epipremnum*, *Ficus* pyramid and then *Ficus* column were perceived to have the highest impact on IAQ. Pparticipant's associated plants with dense canopies and a healthy, lush green appearance as having the most impact on air quality. The canopy density rather than shape appeared to influence the perceived benefit for IAQ. This supports the findings from studies on outdoor plants where bushiness or leaf density has been associated with healthiness (Brascamp, 1996). Dense canopies were also preferred in tree studies and the authors concluded this was because dense canopies indicated a productive environment which was better for survival (V. Lohr & Pearson-Mims, 2006).

Plants with narrow, sharp leaves were perceived as having less impact on IAQ and RH than broad leaved plants, which suggests participants associated the impact on IAQ with leaves and that a higher benefit would be achieved from plants with a greater leaf area. Previous studies have shown that people prefer leafy trees with dense canopies to sparse canopies (Camacho-Cervantes et al., 2014; Nelson et al., 2001) and leaves of moderate length and broader width to narrow ones (Zhao, Xu, & Li, 2017). The most frequently identified benefit, in a study of urban trees, was the improvement in air quality through the addition of oxygen (Camacho-Cervantes et al., 2014).

The scores for perceived benefits for RH were lower than for SWB, and comparable but lower than for IAQ. Participants perceived that the *Epipremnum* and *Ficus* sphere plants would have the greatest benefit for RH, and the neglected palm the least benefit. The characteristics of the plants which would have the greatest benefit for RH were similar to those for IAQ. The lower scores and weaker perceived benefits for RH are possibly due to less familiarity or understanding of the term humidity compared to air quality as there has been considerably less media reporting about the benefits of plants for RH.

Regression analysis revealed that the strongest predictor of IAQ and RH scores was the healthiness of the plant appearance and participants correctly identified that the neglected palm would have significantly the least benefit for IAQ. As the appearance of the plant became more uplifting, interesting, relaxing and beautiful, the respondents perceived there would be a greater improvement in air quality and humidity. Taking into consideration the results of the scoring tests and comments provided, participants have intuitively identified some of the physical characteristics of the physical appearance which will impact IAQ such as leaf area, healthiness and bright green colour. CO_2 is the most common indoor air pollutant and is typically used as an indicator of the overall IAQ (CIBSE, 2011). Previous work (e.g.(Torpy, Irga, & Burchett, 2014; S. V. Pennisi & van Iersel, 2012)) linked the larger plant size/leaf area, healthiness and vigour to better removal of indoor CO_2, which is readily taken up by plants via stomatal pathway, and used in the process of photosynthesis. Findings from Chapters 5 and 6, also showed that more vigorous plants, with greater leaf areas, through just size effect had a more pronounced impact on ambient RH, another component of IAQ (through greater overall ET), in measurement chambers.

The demographics of the participants had very little effect on the preferences or scores for plant appearance or the perceived impact on SWB, IAQ, or RH. Although many plant studies do not report the influence of demographics on results, previous research has shown an effect of gender on preference for plant colours but no effect of demographics on the attitudes and opinions of office workers towards plants in the workplace (Elsadek et al., 2013; Muderrisoglu et al., 2009; Shibata & Suzuki, 2001).

This study supports previous research which showed that indoor plants positively affected people's perceptions of IAQ and environmental quality (van den Bogerd et al., 2021; Nieuwenhuis et al., 2014), but it also advances this area of knowledge by showing that these perceptions and the extent of the perceived benefits are affected by the appearance of the plant.

7.4.2 The effect of plant and leaf shape on preference

The Participants ranked shape as significantly the most important characteristic affecting the attractiveness of a plant's appearance but there was no clear preference for a single canopy shape. In a consumer survey, shape influenced people's opinions about plant attractiveness and their purchasing decisions and the authors related this to the symmetry and bushiness of the plant, (Brascamp, 1996) Participants preferred plants which had canopies with softer, rounded contours whereas plants with spikes, narrow pointed leaves in a sparse canopy, or straight-edged leaves were rated as less beautiful and less relaxing. This may be partially because of the association of sharp edges with danger, in particular concerns about the risk of physical harm from the cactus spikes and sharp pointed leaves of *Dracaena* were highlighted. These results support previous studies of leaf shape where participants preferred rounded natural shapes and considered sharp leaves stressful (Miyake, 2001), less friendly, uglier, less comforting, colder, harder and more dangerous compared to round leaves (Hareli et al., 2016). The palm plant is somewhat of an exception as it has narrow pointed leaves but is also considered beautiful and relaxing, this could be due to the sharp points falling downwards in a gently arching shape, or its association with tropical settings and holidays eliciting a relaxing uplifting response. It is also a very familiar plant and previous studies have shown that frequent exposure can influence preferences, although the effects are complex (Zajonc, 2001; Kaplan & Kaplan, 1989; Herzog, 1987). A previous study of the effect of leaf shape on perceptions of house prices and safety, revealed that sharp-edged vegetation affected how participants viewed other objects in their environment and a protective value was associated with sharp leaved vegetation (Hareli et al., 2016). Additionally the authors also found that palm-like vegetation generated a unique response compared to other sharp leaved vegetation (Hareli et al., 2016).

Previous studies have typically reported an aesthetic preference for the spreading tree shape (V. Lohr & Pearson-Mims, 2006; Summit & Sommer, 1999; Heerwagen & Orians, 1993), which is contrary to the result from this study where the spreading shape was significantly the least preferred. The researchers posited that spreading trees are indicative of rich natural settings which offer survival benefits (V. Lohr & Pearson-Mims, 2006; Sommer, 1997; Heerwagen & Orians, 1993). Our results offer little support for this preference of the spreading canopy shape and are more aligned with studies by Bar and Neta (Bar & Neta, 2006), who found a preference for curved visual objects and proposed that the type of contours influenced people's response to objects. They showed that visual stimuli with sharp angled contours were associated with a feeling of threat or danger and caused increased activity in the amygdala or fear centre in the brain. Although generally curvature elicits increased positive emotions, the response is stimulus and context-dependent, for example people may fear snakes (curved), but like chocolate bars (square-edged) (Bar & Neta, 2007).

7.4.3 Limitations of the research method

Understanding and predicting IAQ and SWB is a complex task and is affected by a multitude of factors. In this study people viewed photographs, whereas their responses may be different when viewing real plants. However, a previous study found oxy-haemoglobin concentrations in the prefrontal cortex increased when subjects viewed real plants, but their emotional responses were similar for both stimuli (Igarashi et al., 2015), suggesting that although physiological responses may be sensitive to the difference in the way the stimuli are presented, subjective and emotional reactions to the plants are adequately and appropriately captured by pictorial stimuli.

Within real indoor spaces, the plant appearance and people's responses may be influenced by the individual aesthetics of particular spaces such as the light levels, colours and spaciousness. Note that our participants provided their responses in multiple different environments over which we had no control, therefore we are confident that our data reflect the average effect over these testing environments, but they do not address how the plants might interact with specific office aesthetics. Indoor plants have been shown to affect other human senses such as through noise reduction (D'Alessandro, Asdrubali, & Mencarelli, 2015) and scent (Qin et al., 2014) which could further affect people's responses and these are not captured here. An interesting area for future study is the reaction not just to plants or pictures of plants in isolation, but to plants embedded within particular settings. Plants in this study were viewed as a singular plant whereas plants in different arrangements may affect people's perceptions; this can be explored in future studies. The majority of participants in the survey reported that they liked indoor plants; this may have influenced their views, although previous surveys have generally reported people are positive about plants in the workplace (Nieuwenhuis et al., 2014; Miyake, 2001).

7.5 Conclusion

This study investigated the psychological responses of 520 participants to the appearance of twelve images of indoor plants. The findings show that the physical appearance of the plant had a significant impact on participants' responses, their aesthetic preference, and the perceived benefit of the plant for subjective well-being, indoor air quality and humidity.

Descriptors of the plant's physical appearance can be used to predict perceptions of its impact on IAQ and SWB. The terms Uplifting, Interesting, Relaxing and Beautiful were the strongest predictors of benefits for SWB. All healthy plants tested were considered beautiful to some extent and to have a positive impact on SWB. The most preferred plants in this study; *Epipremnum, Ficus* sphere, palm *and Ficus* column, were perceived to have the highest SWB benefit. To maximize the well-being benefit for building occupants, designers and installers should choose healthy indoor plants which people find beautiful and interesting.

The perceived benefits for IAQ and RH were most strongly associated with the healthiness, and canopy density of the plant rather than the shape, beauty, or softness of its appearance. Unhealthy plants should be removed from indoor environments as they may negatively impact people's perceptions of IAQ and SWB. The findings of this study show people's perceptions of the indoor environmental quality will be maximized by plants with lush, bright green leaves and high canopy density. These characteristics may also enhance the thermal comfort benefits derived from the presence of indoor plants identified in previous studies (Mangone, Kurvers, & Luscuere, 2014).

Participants identified plant shape as a key characteristic affecting the attractiveness of the plant. There was a preference for plants with rounded contours but there was no clear evidence that participants' preferences or responses were determined by a single canopy shape.

The demographics of the participants had very little effect on the preferences or scores for plant appearance or the perceived impact on SWB, IAQ, or RH. Plant selection for maximum benefit, can therefore remain consistent for environments with different anticipated occupancies.

Depending on the test used and task being undertaken, plant density and location have been shown to affect cognitive performance and productivity of building occupants (Rich, 2008; Shibata & Suzuki, 2002; Larsen et al., 1998). Our results suggest that the appearance of the plants could further influence performance. This study provides new evidence that the appearance of indoor plants can significantly influence people's perceptions of the benefit of plants for indoor air quality, humidity and well-being.

Chapter 8.0

General discussion and concluding remarks

8.1 Introduction

Previous research reviewed in Chapter 1, highlighted the challenges of improving the quality of indoor air for the benefit of building occupants, whilst trying to reduce the carbon emissions from heating, ventilation and air conditioning systems. Indoor plants were identified as a potentially sustainable means of improving IAQ through the reduction of the indoor CO_2 concentration and the addition of water vapour, and so help to alleviate some of the problems associated with IEQ in office environments. In addition, studies showed that adding plants to indoor environments can benefit the psychological wellbeing of building occupants. The literature review revealed the need for further research to understand how the plants performed for IAQ improvements in real office environments and how people might respond to plants with different physical characteristics.

The overarching aim of this research was therefore: to investigate and quantify the potential for potted plants with different traits, to improve the IAQ within indoor office environments, and to determine how the physical traits of the plants affects people's perceptions of their impact on IAQ and their subjective wellbeing.

This research followed a multi-disciplinary approach to investigate these aims and to examine some of the dynamic interactions between the plant, the indoor environment, and the occupant. Through experiments in controlled chambers, real-world office environments and measurements of people's psychological responses this thesis has identified and investigated some of the key factors which influence these (Figure 8.1).

The findings help to further the understanding, about the seasonal variation of IAQ and ACH within a naturally ventilated office in a modular building, and the impact of indoor plants on the CO_2 reduction and the indoor humidity. Furthermore, the studies provide new knowledge showing that the physical appearance of indoor plants affect people's perceptions and emotional responses.

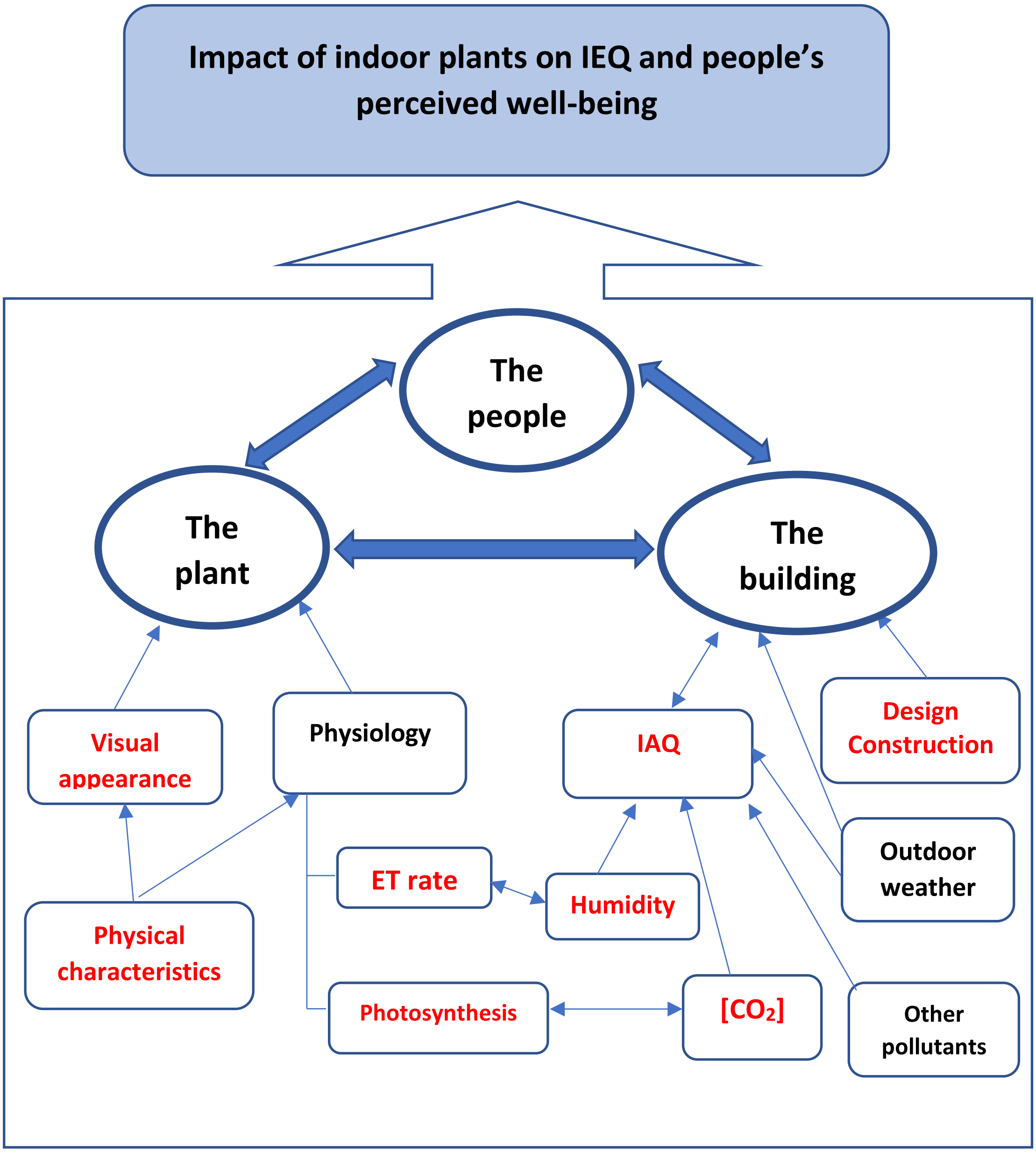


Figure 8.1: Summary of the interaction between the major factors affecting the impact of plants on IEQ and the wellbeing of building occupants. The variables in red were partially investigated in this thesis.

8.2 How did different species and plant density impact the CO_2 concentration in sealed, laboratory-scale chambers ?

The first stage of this research, outlined in Chapter 3, compared the effectiveness of different plant species for reducing CO_2 concentrations in small-scale, sealed chambers before measuring their impact in offices. The LCPs for the plants were determined and, with sufficient light to exceed the LCPs, in the sealed chambers all species with C3 photosynthetic pathway reduced the CO_2 concentrations to some extent whereas *Sansevieria*, a CAM plant, was associated with a net increase of the CO_2 concentration.

CO_2 uptake occurs through stomatal openings in the leaves (Salisbury & Ross, 1992) and experiments in this thesis showed that for C3 plants, increasing the leaf area (and associated stomatal numbers) was positively correlated with increased CO_2 uptake (Chapter 3). However, the results revealed that increasing the leaf area by increasing the plant density in the chamber reduced the CO_2 uptake per plant. Physical characteristics of the plant such as dense and wide arching canopies appear to worsen this effect, indicating the most likely causes of the reduced CO_2 uptake were due to shading effects and changes in the microclimate around the plant (air movement, RH, boundary layer thickness above the leaf) (Runkle, 2016).

The findings showed that the choice of plant species significantly affected the rate of reduction of CO_2 concentration as a result of differences in the plant physiology and physical characteristics such as the size, shape and density of the canopy.

Species selection and planting arrangement were identified as key factors for maximising CO_2 reduction in indoor environments. Attributes such as C3 species, LCPs below the light intensity within the room, high leaf area and planting to avoid shadowing and restrictions of air circulation will maximise the CO_2 reduction from indoor plants. The species with the highest impact identified in this study were *Ficus benjamina* and *Asplenium nidus* and these species were selected for further *in-situ* office-scale experiments for CO_2 reduction.

8.3 How did indoor plants impact the CO_2 concentration in a naturally ventilated office environment, over different seasons?

Environmental conditions at room scale can differ significantly to those in small-scale chambers and the effectiveness of plants for improving IAQ at room scale has been debated in the literature (Cummings & Waring, 2019; Gubb et al., 2018; Torpy, Zavattaro, & Irga, 2017; S.V. Pennisi & van

Iersel, 2012; Llewellyn & Dixon, 2011). Many of the arguments are based on predictions from chamber-scale studies but rarely have the findings been verified in real-world environments where the ACHs of the rooms have been determined. Through the studies conducted in real-world office environments in Chapter 4, significant differences in the impact of plants on the CO_2 concentration were found in offices compared to sealed chambers. Numerous factors which affect the plant performance in real-world environments were identified and the uncertainties associated with extrapolating results from chamber scale to predict rooms scale impact of plants on IAQ were highlighted.

The ACH of a room is a key parameter affecting the IAQ within real-world indoor environments and in naturally ventilated buildings can be subject to considerable variation (Persily, 1989, 2016; Zhang et al., 2015; Persily & Levin, 2011; Awbi, 2003). Experiments in this thesis identified significant differences in the ACHs (where ACH was restricted to air infiltration), determined for five offices, in two naturally ventilated buildings. The building design and type of construction had a major impact on the ACHs, with the offices in an older 1950's construction building having a more variable ACH (up to 90% variation), which was considerably greater than that of the offices in a pre-fabricated, modular building constructed in 2015. There were also differences in the ACHs of comparable offices in the same building depending on the location within the building and the individual fit out of the office. The findings from these studies, support the views put forward by Persily (2016) that ventilation rates are critical in interpreting IAQ measurements and they add further knowledge about the air infiltration rates of naturally ventilated, modular buildings in different seasons.

The office studies also showed that there is a greater variation in the environmental conditions in real-world environments compared to the chambers. For naturally ventilated buildings, outdoor weather conditions can influence the ACH, these studies were therefore conducted on calm weather days and the ACHs within experimental offices measured for each season. The results showed that, although not statistically significant, there was a seasonal variation in the room ACH and the rate of CO_2 reduction by the plants; the highest ACHs and rates of CO_2 reduction were measured during the summer. In these experiments the presence of either 12 *Ficus* plants, six *Asplenium* plants or six *Epipremnum* plants did not have a measurable, significant impact on the rate of reduction of CO_2 from a starting concentration of 2000 ppm, within the offices during the daytime in winter, spring or summer compared to the days without plants. It is possible that a proportion of the reduction in CO_2 concentration was due to CO_2 uptake by the plants, but this was insignificant compared to the amount removed through air exchange (infiltration) and the associated variation. The CO_2 concentration reductions by the plants, measured during the small-scale chamber studies in Chapter 3, were not verified in the office scale studies. Overall, it was determined that the building design and construction, and environmental factors (including seasonal changes) had a greater impact on the rate of CO_2 reduction from the offices than the presence of the plants in the numbers we tested. Some of the factors influencing the overall impact of plants on indoor CO_2 concentrations are summarised in Figure 8.2.

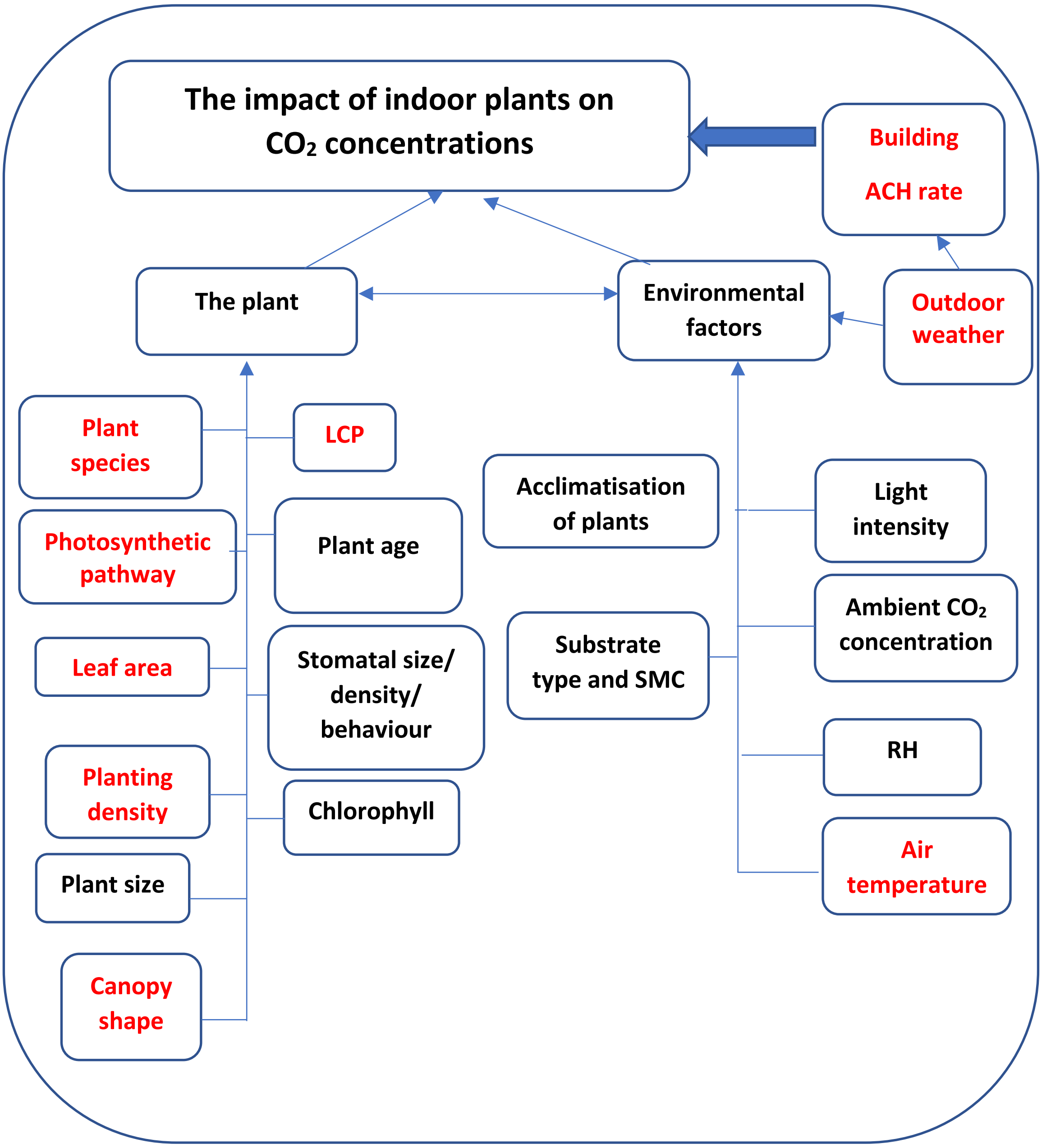


Figure 8.2: Summary of the interaction between the major factors affecting the impact of indoor plants on [CO_2] reduction. The variables in red were partially investigated in this study.

Potted plants and chamber-scale studies remain a valuable area of study to find out more about the performance of individual species and the factors which influence them under controlled conditions. However, when estimating the impact of indoor plants at room scale it is essential that researchers consider the ACH and the actual environmental conditions.

The uptake of CO_2 by one potted plant measured in these experiments was less than one per cent (approximately 0.2 g h^{-1} $plant^{-1}$) of the amount typically exhaled by a sedentary office worker (approximately 32 g h^{-1} $person^{-1}$) (Persily & de Jonge, 2017). Adding more plants is one way to reduce CO_2 concentration within a room but this raises practical issues. In this study 12 Ficus plants occupied 3% volume of the office and a considerable amount of desk space which would be impractical for someone working in the office. Very high numbers of plants (22 plants occupying 18% of office volume) may also distract office workers from certain tasks and could potentially reduce their productivity (Larsen et al., 1998). Indoor green walls, have been identified by other researchers as offering greater potential for the future use of indoor plants for CO_2 reductions (Torpy, Zavattaro, & Irga, 2017; Su & Lin, 2015). The findings from this thesis support this direction of research, as a greater leaf area can be incorporated into a smaller floor area with specialised lighting to help increase the rate of photosynthesis

8.4 How did the air temperature and RH affect the ET rates of different indoor plant species?

The 'humidification potential' of indoor plants depends on their ET rate. Factors which influence this (such as species and environmental conditions), will therefore affect the impact the plants have on the indoor air humidity. Two key parameters of indoor environments that affect the comfort of building occupants, T_a and RH, can also impact plant ET rates. The focus of Chapter 5 was therefore to compare how different conditions of T_a and RH, representative of typical office environments, influenced the ET rates of different species of indoor plants in controlled environmental chambers.

The results showed that there were significant differences in the ET rates between the five plant species tested under all environmental conditions ('warm', 'hot', 'cool', 'dry', 'humid'). *Epipremnum* had the highest ET rate under all conditions, so was identified as having the greatest 'humidification potential' for indoor environments. *Sansevieria* had the lowest ET rate, with 95% of the water loss occurring from the growing medium, this species would therefore be expected to have the least potential for humidifying dry indoor air but would be a good choice for environments where a low moisture contribution is required.

The environmental conditions of T_a and RH had a significant impact on the ET rate of the plants, but the size of the effect was species-dependent. All plants had the greatest water loss under 'dry' (low RH, or high VPD) conditions. The ET rates decreased with increasing RH and with decreasing T_a and the lowest ET rates were under 'humid' (high humidity, low VPD) conditions. In indoor environments, the water vapour contribution of the plants is therefore likely to decrease as the air humidity level increases.

Both physical and physiological characteristics influenced the ET rate of the plants. Greater plant leaf area was associated with higher ET rates, but comparison of ET rates on a unit of leaf area basis showed inherent differences between species. *Calathea* had the highest ET rate per square metre of leaf area, but it had a lower leaf area per plant compared to other plants and so a greater quantity of plants would be required to equal the leaf area of other species. Based on the findings of previous studies, stomatal size, density and response are likely to account for some of the differences in ET rates between species (Lawson & Vialet-Chabrand, 2019; Panyametheekul et al., 2019). As the stomata control both ET rate and photosynthesis, factors which affect the stomatal response for CO_2 uptake, including light intensity, will also influence ET rate. Comparisons of the ET rates under light (20 µmol m^{-2} s^{-1} in our experiment) and dark conditions highlighted differences between CAM and C3 species; all C3 plants had higher ET rates under light conditions whereas *Sansevieria*, a CAM plant, had a higher ET rate under dark conditions. To maximize the daytime water vapour contribution from indoor plants, C3 plant species should therefore be selected.

Similar to the findings from the studies of CO_2 reduction, there is a complex interaction between the plant, the environmental conditions (T_a, RH, light intensity, and water availability) and the ET rate. The findings showed that species selection and leaf area are of major importance when considering the use of indoor plants for room humidification purposes, either for increasing the room humidity or minimising the risk of condensation formation. The greatest impact from plants on indoor humidity levels is likely to be within hot, dry, brightly lit indoor environments and the least impact will be in cool, humid, dark environments. The choice of plant species can be tailored to suit different humidification requirements or environmental conditions. To maximize the moisture contribution from plants, C3 plant species with high ET rates and high leaf area (high stomatal numbers) should be selected. From a practical maintenance viewpoint, however, plants with low ET rates would be expected to minimise water use for plant maintenance and reduce the frequency of watering required.

8.5 How did indoor plants impact the temperature and humidity in a naturally ventilated office environment over different seasons?

Previous studies have estimated a wide variation in the impact of indoor plants on room humidity, ranging from no impact to 10% increase in RH over 24 hours (Tudiwer & Korjenic, 2017; Su & Lin, 2015; Mangone, Kurvers, & Luscuere, 2014; Smith & Pitt, 2011; Wood et al., 2006) but typically ACHs, and changes in T_a and RH have not been considered. To contribute to this knowledge gap, Chapter 6 investigated how plants with high ET rates affected the T_a and AH in office environments over different seasons and if the performance of the plants at chamber scale was verified at room scale.

The three species of plant tested, *Ficus benjamina, Asplenium nidus* and *Epipremnum aureum,* contributed between 35-68 g of water vapour, per plant, per day to the indoor office air through ET depending on the species and environmental conditions. The ET rates of the plants were lower in the offices compared to the controlled environment chambers and there was significant seasonal variation in both the office T_a and RH, and in the ET rates of the plants. The plants emitted 66% more water vapour during warm summer days compared to cool winter ones and the T_a and AH in the office were 10-50% higher during the summer compared to winter or spring. The higher summer ET rates can be partially explained by seasonal differences in the VPD within the offices, which increased from winter to summer, as the chamber studies in Chapter 5 and other studies (Kemp, Hadley, & Blanusa, 2019) showed a positive correlation between VPD and ET rate. The seasonal differences may also have been due to changes in plant physiological activity (photosynthesis and transpiration) in response to seasonal changes in day length, light intensity, light wavelength and colder nights which has been shown in previous studies (Cai et al., 2020; Li et al., 2019; Salisbury & Ross, 1992).

The findings also showed that whilst the plant ET rate differed at room scale compared to the chambers, so too did the impact of the emitted water vapour on the office air humidity. This was shown to be dependent on two key factors: the air flow rate of the room, and the indoor and outdoor environmental conditions, which showed seasonal variation. In spring, the addition of 12 *Ficus* plants, resulted in a small but significant increase in the AH of Office 1 whilst in summer although the plants emitted more water vapour, this resulted in a small but non-significant increase in AH. This difference can be partially explained by the higher ACH of the office during summer, resulting in more water vapour being removed. In the winter experiments, the introduction of six *Epipremnum* plants, was associated with a small but significant increase in the

AH whereas 12 *Ficus* plants or six *Asplenium* plants had no significant impact, highlighting the difference between species.

For all seasons, the increase in AH within the office was considerably lower than the amount of water vapour emitted by the plants. Between 65% -100% of the water vapour emitted by the plants was lost through the air exchange and through absorption by the materials within the room. The impact of plants on indoor humidity depends on the ACH of the room but also on the absorption/desorption properties of the materials and internal finishes within the room.

The findings from these experiments did not determine any cooling effect from the addition of plants in the offices, although this was found in previous studies using indoor living green walls (Pérez-Urrestarazu et al., 2016; Fernández-Cañero, Urrestarazu, & Franco Salas, 2012). In our study, it is likely that any reductions in T_a from the plants were localised around the plant and insignificant compared to the heat gains from other sources such as the air exchange, central heating and lighting. Furthermore, indoor green walls have a larger leaf area and active green walls force an air flow over the plant leaf surface which will aid transpiration.

From the occupant's viewpoint, the studies were conducted with the doors, windows and trickle vents of the rooms closed, resulting in very low ACHs in Building 2, with air supply rate equivalent of 7.7 $m^3 h^{-1}$ approximately, compared to the recommended industry guidance of 36 $m^3 h^{-1}$ (UK Government, 2010). The mean daytime T_a was between 17.5-26.5°C, which is within the recommended range for office workers and the RH ranged between 50-71% RH without any occupants in the room, which reaches the maximum of 60-70% RH recommended for office worker comfort (British Standards, 2011; CIBSE, 2006b). Whilst thermal comfort wasn't measured in this study, occupants working in these offices without plants, and with the ventilation closed are likely to feel thermal discomfort and experience stuffiness of the air and raised CO_2 levels. This highlights the challenges for building designers, that increasing airtightness of buildings to minimise heat loss can negatively impact IEQ, particularly when relying on manual operation of the ventilation sources such as trickle vents and opening windows.

The plants in this study emitted approximately 2-3 g of water vapour $plant^{-1} hr^{-1}$ in the office environment. By comparison one human contributes between 30 -90 g hr^{-1} $person^{-1}$, (CIBSE, 2006a), and household activities such as washing, drying, bathing and cooking can add from 200-5000 g of moisture per day (CIBSE, 2006a). The contribution of plants is therefore very small in comparison to other sources but can have a more significant impact with a greater number of plants. The offices used in this study had a tendency towards high relative humidity levels and from Chapter 5 and other studies, it is known that plant ET rates increase at low humidity, thus it would be anticipated the plants would emit more water vapour in dry indoor environments where increased humidity is desired. These offices also have a very low ACH, and in offices with higher ACH the impact of the plants on AH would be reduced as more moisture would be removed.

The moisture concentration of the air within buildings is a complex phenomenon to measure as it depends on many interacting factors (e.g. T_a, ACH, outdoor RH, adsorption/desorption properties of the materials). This study provides new evidence that indoor plants can have a small but significant impact on the AH within naturally ventilated office environments. The findings showed that the impact varies with the plant species, it is influenced by the environmental conditions and seasonal variation. A limited number of previous studies have reported the impact of indoor plants on indoor humidity (Torpy, Zavattaro, & Irga, 2017; Pérez-Urrestarazu et al., 2016; Su & Lin, 2015; Mangone, Kurvers, & Luscuere, 2014; Fernández-Cañero, Urrestarazu, & Franco Salas, 2012) but this is the first study to the author's knowledge which has investigated in detail the seasonal variation and dynamic interaction between the plant ET rate, the indoor AH and the ACH within a naturally ventilated office.

8.6 How were people's preferences and responses influenced by the appearance of indoor plants displaying different physical characteristics?

The evidence from experimental work in Chapters 3-6, and other research (Gubb et al., 2018; Torpy, Irga, & Burchett, 2014; S.V. Pennisi & van Iersel, 2012) show that the impact of individual potted plants on IAQ parameters (CO_2 reduction and RH) at a room scale is relatively small. However, there is little understanding about people's psychological response to the appearance of different indoor plants. To contribute to this knowledge gap, Chapter 7 investigated the psychological responses of 520 participants to twelve images of indoor plants through a photo-questionnaire.

The findings showed that the physical appearance of the plant had a significant impact on participants' responses, their preferences, and perceptions. The demographics of the participants had very little effect on the preferences or scores for plant appearance or the perceived impact on SWB, IAQ, or RH.

There were individual differences, but overall, there were four most preferred plants: *Epipremnum aureum, Ficus benjamina* (sphere shape), *Dypsis lutescens* (palm) *and Ficus benjamina* (column shape). Interest as well as beauty affected participants preferences, and *Epipremnum* which had leaves on trailing vines, was reported as significantly more interesting.

Plant shape was identified as a key characteristic affecting the attractiveness of the plant and more beautiful plants were associated with rounded leaves and softer canopy edges but there was no clear preference for a single canopy shape. Previous studies of trees had shown a preference for spreading canopy shapes (V. Lohr & Pearson-Mims, 2006; Summit & Sommer, 1999; Heerwagen & Orians, 1993), which was not found in this study suggesting indoor plants are viewed differently to trees as our results were more aligned with studies by Bar and Neta (2006), who found a preference for curved visual objects.

The healthiness of the plant, such as dark green colour and dense canopy, appeared to increase its perceived beauty and the physical characteristics of the plants affected participants' responses. Some physical traits such as prickles, sharp edged leaves and striped patterns evoked more diverse responses, for some participants they were associated with danger whilst others found them fascinating. The findings suggest that plants with differing physical characteristics could be used to change the appearance and feel of a space. For example, soft shapes such as the spherical *Ficus* or gently arching palm plants could be used to create a relaxing atmosphere, whereas plants with solid, upright pointed shapes or sharp edged leaves, such as *Sansevieria c*ould be used to infer strength and security. Plants with a dramatic appearance, such as *Calathea* , would be appropriate as feature plants to generate a more fascinating focal point.

8.7 How did the physical appearance and shape of the plant affect people's perception of its impact on IAQ, RH or SWB?

There was a positive correlation between participants' emotional responses, preferences, and perceived wellbeing. Participants had greater preference for plants which they found attractive, healthy, and interesting, and they perceived these would have the greatest benefit for their SWB. To investigate how people's perceptions of the benefits of different plant species for SWB, IAQ and RH compared to the actual measured impact of the plant the findings of Chapter 7 and Chapters 3 and 5, have been plotted in Figures 8.3 and 8.4

For the purposes of these comparisons, scores for IAQ have been related to the reduction of CO_2 concentration per plant per hour, and impact on RH has been related to the ET rate of the plant per day, although participants may have interpreted these terms and scores differently. For *Ficus*, participants' scores for *Ficus* column were used as this was the plant used in the experiments.

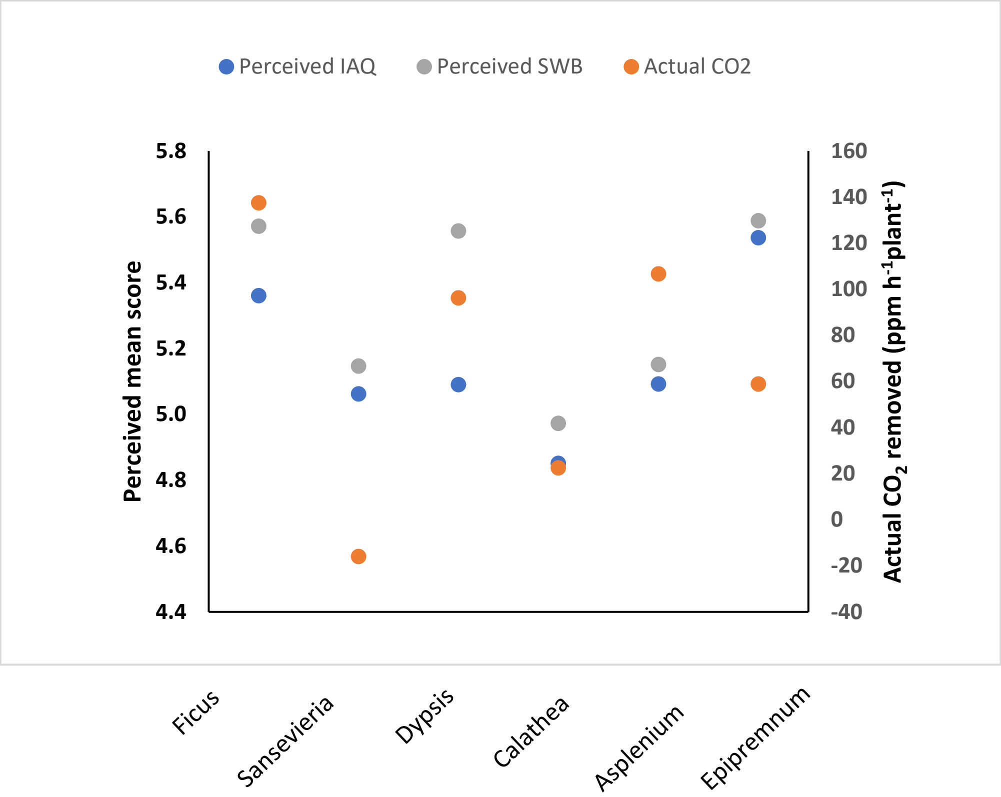


Figure 8.3 : Comparison of perceived impact of plant species on IAQ and SWB against the actual CO_2 reduction capacity of the plant. "Perceived benefit" are participants' mean scores for IAQ and SWB obtained in the survey (N=520) in Chapter 7 (maximum =7, minimum=1), and "Actual " is the CO_2 reduction rate for each plant (ppm h^{-1} $plant^{-1}$) measured in Chapter 3.

Participants' scores for perceived benefits of the plants for SWB were higher than those of IAQ and RH. From Figures 8.3 and 8.4, it appears that participants' perception of the comparative impact of the plants on humidity showed good correlation with the actual ET rates, as the species were placed in the same rank order for both measures. The perceptions for IAQ are less well correlated with the actual impact on CO_2 reduction; participants ranked the impact of *Epipremnum* and *Sansevieria* higher than their actual impact, compared to other species, whereas the impact of *Dypsis* (palm), *Ficus* and *Asplenium* were ranked comparatively lower. The differences in scores between IAQ and RH may be due to unfamiliarity or different understanding of the terms humidity and air quality as these were not explicitly defined to the survey participants.

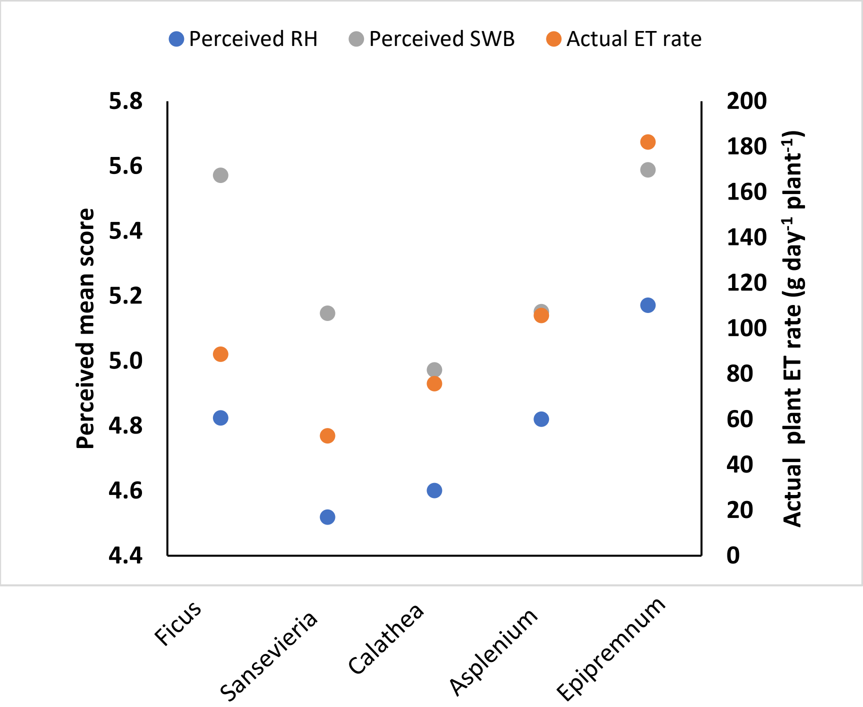


Figure 8.4 : Comparison of perceived impact of plant species on humidity and SWB against the water vapour emitted from the plant. "Perceived" are participant's mean scores for RH and SWB obtained in the survey (N=520) in Chapter 7, and "Actual " is the ET rate for each plant (g day^{-1} plant^{-1}) measured in the environmental chambers in Chapter 5.

The survey results showed that, the perceived wellbeing benefits for plants were associated with the perceived interest and beauty of the plant and participants preferences, whereas for IAQ and RH, the perceived benefits were most strongly associated with the healthiness and canopy density of the plant. As the appearance of the plant became more uplifting, interesting, relaxing and beautiful, the respondents perceived there would be a greater improvement in air quality and humidity.

People perceived that plants with narrow, sharp leaves would have less IAQ and RH benefit than broad leaved plants and thicker canopies, suggesting participants associated the IAQ with leaf area.

Overall, participants appear to have intuitively identified some of the physical characteristics of the physical appearance which have been identified in Chapters 3 and 5 and previous work which will positively impact IAQ such as leaf area, healthiness and bright green colour (e.g. (Torpy, Irga, & Burchett, 2014; Pennisi & van Iersel, 2012)).

An important finding from the comments and scores in the survey, is that plant healthiness affects perceived wellbeing benefits whereas an unhealthy plant was perceived negatively for wellbeing and IAQ impacts.

Previous research has shown that indoor plants positively affected people's perceptions of thermal comfort, IAQ and environmental quality (van den Bogerd et al., 2021; Mangone, Kurvers, & Luscuere, 2014; Nieuwenhuis et al., 2014). This thesis advances this area of knowledge by showing that these perceptions and the extent of the perceived benefits are affected by the appearance of the plant. Plants with high ET rate, high leaf area and high score for perceived RH/IAQ improvements could potentially lead to enhanced thermal comfort benefits for building occupants.

8.8 Key findings and contributions to knowledge

Indoor plants are introduced into buildings to benefit the occupants, either through improvements to the air quality, to enhance the space, or to benefit their wellbeing. This thesis investigated some of the complex, dynamic relationships between the building, the plant, the indoor air quality and the occupants. The results from experiments in controlled chambers, real-world office environments and measurements of people's psychological responses, the influence of some of the key factors affecting the impact of the plant on aspects of the IAQ and people's perceived wellbeing have been identified.

The key findings have been discussed above and within each chapter. Some of the original contributions to knowledge this thesis has made include:

- Quantifying the psychological response of 520 participants to indoor plants - revealing that the physical appearance can significantly influence people's preferences and perceptions of the benefit of plants for IAQ, humidity and SWB.
- Identifying that plant health, canopy density, interest and beauty are key characteristics affecting people's perceptions of IAQ and SWB benefits, whereas unhealthy plants may have a negative impact.
- Quantifying the moisture contribution to indoor air of indoor plants at both chamber-scale and office-scale - identifying significant differences between species and environments.
- Determining the impact of varying ambient T_a, RH on ET rates and identifying seasonal variations of ET within a naturally ventilated office – the highest ET rates were in summertime or hot, dry environments and lowest rates in cool, humid conditions.

- Quantifying the CO_2 reduction of indoor plants at both chamber-scale and office-scale - identifying that at chamber-scale, C3 plants reduced CO_2 concentrations but species selection, LCP, leaf area and planting density impacted the CO_2 removal efficiency.
- Determining that in a naturally ventilated office, the air flow rate and environmental factors, had a greater impact on the rate of CO_2 reduction than the presence of the plants.
- Providing new insight into the seasonal IEQ within a pre-fabricated, modular building and identifying significant impact of building design and construction through detailed characterisation of the ACHs, Ta, and RH within naturally ventilated offices.

Experiments conducted as part of this thesis provide new data to help inform the choice of the best species for indoor humidification and CO_2 reduction, and new evidence that the appearance of indoor plants can significantly influence people's perceptions of the benefit of plants for indoor air quality, humidity and wellbeing. The findings can help future researchers in designing experiments to measure the impact of plants at room-scale.

The findings can assist designers, architects, building managers and homeowners in choosing plants which have maximum benefit for the health and wellbeing of building occupants and to create different aesthetic environments.

8.9 Future Work

This work identified the importance of the physical appearance of the plant on people's emotional responses and perceptions, but participants assessed images of a relatively small number of plants compared to the vast range of species available. More studies are needed to investigate responses to a wider range of plant species and characteristics. Furthermore, participants assessed images of plants and further studies are needed to determine their responses to real plants, in real-life settings so that the participants can also consider the relative size of the plants.

Participants in this study perceived that the appearance of the plant would influence its impact on IAQ, RH and SWB. Previous studies have shown that thermal comfort is partially due to a psychological response, and it is possible that people's thermal comfort may therefore be influenced by the appearance of the plant. Further investigation of how plant characteristics influence people's thermal comfort in different environments would be useful as the selection of different plant species may be able to improve people's comfort in 'challenging' environments.

Participants perceived that most green plants would benefit their SWB, but people's wellbeing is affected by many factors, and it is not possible from these results to isolate the effect of plants from other influences. Further studies would be useful to contrast the wellbeing effects of indoor plants compared to other aspects of the office design and factors affecting the working conditions such as the workload.

Participants cited shape as the most important characteristic affecting the attractiveness of plants. People's responses to planting arrangements would therefore be useful as these are used in many commercial installations.

People's response to neglected plants warrants further investigation. In this study only one neglected plant was included which participants perceived would have a negative impact on their SWB. A more detailed understanding of the response to different types of sick or poorly maintained plants is needed. People's response to artificial plants were not investigated in this study but are worthy of future investigation – artificial plants require less maintenance, but it is not clear if they would evoke the same perceived wellbeing benefits as live plants. Further investigation of the impact of artificial plants on people's responses and perceptions would also be useful.

The impact of indoor plants on IAQ at room-scale is small and therefore optimizing species selection to maximise the impact of the plant is essential. For CO_2 reduction and addition of water vapour, the stomata play a key role. Further research about the stomata in indoor plants (size, density and response rates for both photosynthesis and ET) would be useful to assist with the selection of species which are likely to have the most impact on IAQ.

These studies were conducted at 2000 ppm CO_2 concentration to mimic the concentrations found in an office environment with high occupancy. Few indoor plant studies have investigated the response of plants to different CO_2 concentrations although these vary with occupant density and their activities. Further investigation of the influence of high CO_2 concentration on the stomatal response, photosynthesis and transpiration would be useful to understand more about the response of the plant in different environments.

In this study measurements of the impact of the plants on humidity were made in offices within a modern modular building which had relatively high RH levels. The greatest potential for high ET rates and the greatest need for addition of water vapour is in dry indoor environments. Further real-world studies are therefore needed in hot, dry, indoor environments, using plants with high ET rates to add more understanding about the humidification potential of indoor plants.

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Appendix 1

The following are examples of questions used in survey, images of twelve plants were shown separately one at a time. Participants clicked after completing the questions about each pant and the next image appeared. For simplicity examples of only two plants are included here.

Welcome.

You are invited to participate in this survey and to give your opinions on the appearance of indoor plants.

This is part of a larger research project on indoor plants and healthy building design which is being conducted by Jenny Berger, a PhD student, from the School of the Built Environment at the University of Reading. It should take no more than 10 minutes to complete. Please submit the form online or return it to: Jenny.berger@pgr.reading.ac.uk by 30 June 2021.

Please note your participation is voluntary. You do not have to complete all of the questions and you can stop at any time. Responses are confidential and anonymized. Your participation will not be mentioned within any publication or presentation resulting from this survey. By completing and returning this survey you understand that you are giving consent for your responses to be used for the purposes of this research project.
If you have any questions or concerns, or you would like to see a summary of the findings, please contact jenny.berger@pgr.reading.ac.uk or my supervisor at e.a.essah@reading.ac.uk

Thank you for your support.

Jenny Berger

Do you like indoor plants? (tick all that apply)

☐ Yes in my home
☐ Yes in the workplace
☐ I became interested since lockdown
☐ No

Do you enjoy looking after indoor plants? (tick all that apply)

☐ Yes -at home
☐ No - at home
☐ Yes - in the workplace
☐ No - in the workplace

Do you have a background in any of the following areas?

○ Environmental / Horticulture / Agriculture / Biology
○ Architecture / Construction
○ Art/ Design

Do the buildings you live or work in have connections with or views of nature such as plants or trees?

○ Yes - a lot
○ Yes - a little
○ No

You will now be shown a total of 12 separate pictures of indoor plants. Thinking of the plant in your office, workspace or home please give your opinion of each plant.

Q4. What do you think of the appearance of the plant?

Plant 1 of 12

Ugly	O	O	O	O	O	O	O	O	Beautiful
Boring	O	O	O	O	O	O	O	O	Interesting
Sharp	O	O	O	O	O	O	O	O	Soft
Unhealthy	O	O	O	O	O	O	O	O	Healthy
Stressful	O	O	O	O	O	O	O	O	Relaxing
Uplifting	O	O	O	O	O	O	O	O	Depressing
Ugly	O	O	O	O	O	O	O	O	Beautiful
Boring	O	O	O	O	O	O	O	O	Interesting

Q5. What benefit do you think the plant would have for the following?

	High							**Low**
Air quality	O	O	O	O	O	O	O	O
Humidity	O	O	O	O	O	O	O	O
My well-being	O	O	O	O	O	O	O	O

Q6. What do you think of the appearance of the plant?

Plant 2 of 12

Ugly	○	○	○	○	○	○	○	○	Beautiful
Boring	○	○	○	○	○	○	○	○	Interesting
Sharp	○	○	○	○	○	○	○	○	Soft
Unhealthy	○	○	○	○	○	○	○	○	Healthy
Stressful	○	○	○	○	○	○	○	○	Relaxing
Uplifting	○	○	○	○	○	○	○	○	Depressing
Ugly	○	○	○	○	○	○	○	○	Beautiful
Boring	○	○	○	○	○	○	○	○	Interesting

Q5. What benefit do you think the plant would have for the following?

	High							**Low**
Air quality	○	○	○	○	○	○	○	○
Humidity	○	○	○	○	○	○	○	○
My well-being	○	○	○	○	○	○	○	○

Q28

Overall which three plants did you prefer? - please enter plant number in the box

○ 1st choice ____

○ 2nd choice ____

○ 3rd choice ____

Q29

Which plant did you least prefer?

○ Last choice ____

Q30. Please rank the following factors in order of importance to you, when considering the attractiveness of indoor plants (drag the factors to required order)

______ Colour
______ Overall plant shape
______ Leaf shape
_____ Texture
______ Leaf pattern

Q31. Is there anything you would like to add about your opinions on indoor plants?

(free text box inserted here)

Q32
You've almost finished, before you go we just need a few details about you to help us understand the findings.

What is your gender?

- ○ Female
- ○ Male
- ○ Other
- ○ Prefer not to say

Q33 What is your age group?

- ○ Under 25
- ○ 25-34
- ○ 35-49
- ○ 50-64
- ○ 65+
- ○ Prefer not to say

Q34 Which of these best describes your current occupation

- ○ Professional (e.g. Lawyer, Accountant, Engineer, Senior manager)
- ○ Teaching / Education
- ○ Administrative / Secretarial
- ○ Healthcare
- ○ Other business role
- ○ Skilled trades or vocational roles
- ○ Student
- ○ Retired
- ○ Other

Q35 Where do you currently spend most of the working day?

- ○ At home - working or other
- ○ Working in an office
- ○ Working or studying indoors in another type of building
- ○ Mobile or outdoor work
- ○ Other

End of Block:

Appendix 2

		Ugly-Beautiful	Boring-Interesting	Sharp - Soft	Unhealthy-Healthy	Stressful-Relaxing	Uplifting - Depressing	IAQ	RH	SWB
Ficus column	M	5.4	4.8	4.9	5.9	5.5	2.8	5.4	4.8	5.6
	SD	1.2	1.5	1.3	1.2	1.3	1.4	1.5	1.5	1.3
Sansevieria	M	4.7	4.9	2.6	4.6	4.0	3.2	5.1	4.5	5.1
	SD	1.6	1.6	1.4	1.8	1.6	1.4	1.6	1.6	1.5
Cactus	M	4.5	4.9	1.8	5.4	4.2	3.5	3.7	3.5	4.6
	SD	1.7	1.8	1.4	1.5	1.6	1.5	1.8	1.8	1.7
Ficus sphere	M	5.5	5.2	5.3	5.9	5.5	2.8	5.6	5.1	5.7
	SD	1.4	1.5	1.3	1.2	1.3	1.6	1.4	1.5	1.2
Ficus pyramid	M	5.2	4.9	5.0	5.8	5.3	3.0	5.5	5.0	5.5
	SD	1.4	1.6	1.4	1.2	1.3	1.5	1.4	1.5	1.3
Neglected palm	M	3.2	3.9	3.6	2.8	3.3	4.9	3.2	3.1	3.2
	SD	1.7	1.8	1.7	1.7	1.6	1.7	1.9	1.8	1.8
Palm	M	5.5	5.2	3.8	5.9	5.4	2.8	5.1	4.6	5.6
	SD	1.3	1.5	1.7	1.1	1.4	1.5	1.5	1.6	1.3
Spreading *Ficus*	M	5.1	4.9	4.9	5.6	5.2	3.0	5.2	4.8	5.4
	SD	1.4	1.5	1.2	1.3	1.2	1.3	1.4	1.5	1.3
Calathea	M	4.7	5.0	5.0	4.9	4.7	3.4	4.9	4.6	5.0
	SD	1.6	1.6	1.3	1.6	1.4	1.5	1.5	1.5	1.5
Asplenium	M	4.7	4.6	4.9	5.5	5.0	3.2	5.1	4.8	5.2
	SD	1.5	1.7	1.4	1.3	1.3	1.4	1.5	1.6	1.4
Epipremnum	M	5.3	5.5	5.5	5.4	5.4	2.9	5.5	5.2	5.6
	SD	1.6	1.5	1.3	1.7	1.4	1.6	1.4	1.5	1.4
Dracaena	M	4.9	5.0	2.8	5.5	4.7	3.2	4.6	4.3	5.1
	SD	1.5	1.6	1.5	1.2	1.4	1.4	1.6	1.6	1.5

Table 7.6: Results of the bipolar scales, showing mean scores (M) and standard deviation (SD) for each descriptor and plant. (Mean is the average of 520 responses)