Indoor living plants' effects on an office environment

Structured Abstract

Purpose
The use of indoor living plants for enhancement of indoor relative humidity and the general environment of a large, modern, open plan office building; are studied using a mixed-methods paradigm.

Design/methodology/approach
The quantitative element involved designated experimental and control zones within the building, selected using orientation, user density, and users' work roles criteria. For a period of six months, relative humidity was monitored using data loggers at 30-minute intervals and volatile organic compounds (VOCs) were measured using air sampling. Qualitative 'perception data' of the building's users, were collected via a structured questionnaire survey among both experimental and control zones.

Findings
Study findings include that living plants did not achieve the positive effect on relative humidity predicted by (a-priori) theoretical calculations; and that building users' perceived improvements to indoor relative humidity, temperature, and background noise levels, were minimal. The strongest perceived improvement was for work environment aesthetics. Findings demonstrate the potential of indoor plants to reduce carbon emissions of the [as] built environment, through elimination or reduction of energy use and capital-intensive humidification air-conditioning systems.

Originality/value
The study's practical value lies in its unique application of (mainly laboratory-derived) existing theory in a real-life work environment.

Keywords: Indoor air quality, Comfort, Temperature, Volatile organic compounds, Living plants, Relative humidity

Article classification: research paper

1. Introduction

Indoor air quality (IAQ) of commercial and domestic buildings has been widely researched over the past three decades. Studies have focussed on aspects such as respiratory irritants, for instance, nitrogen and sulphur dioxides (Taylor, 1996; Chao, 2001; Meininghaus *et al*, 2003; Baur *et al*, 2012); carcinogens such as asbestos (Reynolds *et al*, 1994; Latif *et al*, 2011; and other volatile organic compounds (VOCs) such as formaldehyde (Wolverton and McDonald, 1982; Ekberg, 1994; Meininghaus *et al*, 2003; Zuraimi *et al*, 2006; Rios *et al*, 2009; Salonen *et al*, 2009). Research has also investigated optimum percentage relative humidity (%*RH*) of indoor air (Wyon *et al.*, 2002; Wolkoff and Kjaergaard, 2007; Wan *et al.*, 2009); this being the ratio of percentage water vapour held within it to its equivalent 'saturation level' at a given temperature. This study extends these concepts in terms of their being influenced by the introduction of indoor living plants, in a large modern building. The building users' perceptions of their internal environment in relation to these plants, are also considered.

Typically, humidity is not classified as an indoor air contaminant (Nagda and Hodgson, 2001). Nonetheless, many studies (for example, Wyon *et al.*, 2002; Wolkoff and Kjaergaard, 2007; Wan *et al.*, 2009) and building design guides (CIBSE, 2005; 2006), recommended that indoor %*RH* should be in the range of 40-60%. Beyond these parameters there are negative health implications for building inhabitants as described in the literature review later; and for levels above the maximum recommended *RH* value especially, there are additional risks of building (components') damage. Examples of this include material expansion, salt staining, corrosion, pattern staining, interstitial condensation, and fungal growth (CIBSE 2005; Hetreed, 2008; Oxley and Gobert, 2011).

Mechanical humidity control is available, but the use of living indoor plants for this purpose is much less researched or understood (existing studies include Costa and James, 1995; Wolverton and Wolverton, 1996). The primary aim of this study therefore, is to investigate the potential of plants to supplement indoor air relative humidity (*RH*), during cold winter months. This is important because decreasing air temperature reduces the ability of air to hold water vapour. Hence, as cold air from ventilation is heated up to indoor temperature, its ability to retain water vapour increases, resulting in a proportionate decrease in its relative humidity. This could lead to prolonged periods of below recommended indoor %*RH* and the resultant associated problems such as occupant discomfort (addressed in the literature review below).
The study was undertaken empirically, where indoor %*RH* was measured over a period of six months in a large (approximately 10,300m^2 gross floor area), modern 'atrium design' office

building. The building was selected as a case study, because its facilities management were investigating low carbon and sustainable methods of humidification, during the winter months. An objective linked to this aim, was to compare these empirical data with those of theoretical a-priori calculations. The latter ‘predicted’ the humidification effect of indoor plants as a product of their plant transpiration rates and foliage area, to identify an ‘ideal’ indoor planting density. The building users’ perceptions of (the introduction of) indoor plants were sampled in relation to humidity, temperature, noise, light, space, aesthetics, and working environment privacy.

2. Literature review

Indoor relative humidity <30%*RH* is only acceptable for limited periods of time, otherwise, building occupants can become prone to allergies and respiratory illnesses due to dust and other airborne particles (CIBSE, 2006). At significantly low levels of humidity, Bron *et al.* (2004) reported a change in the precorneal tear film in humans’ eyes, that results in discomfort (dry eyes), while Doty *et al.* (2004) reported sensory irritation of the upper airways. Wyon *et al.* (2002) identified that human skin exposed to 15%*RH* was significantly drier than the same skin exposed to 35%*RH* and associated this kind of health symptom, with the classic definition of sick building syndrome.

More recently, Wolkoff and Kjaergarrd (2007) confirmed that the health implications of indoor humidity are complex. Further, that these have not been widely investigated due to the complicated influence of *RH* on the combined impact of VOCs and other indoor air contaminants. Low humidity levels are also associated with susceptibility to electrostatic shocks. Human body voltage is a function of indoor air such that a decline in %*RH* yields an increase in body voltage (CIBSE, 2006) – a situation exacerbated in buildings with a combination of underfloor heating and carpet flooring due to sustained dryness of carpets.

Higher *RH* levels are associated with poor ventilation and/or significant evaporation from moisture sources (such as bathrooms, kitchens, and indoor plants). High humidity can also lead to surface (or interstitial) condensation on (or within) external walls and other building fabric whose temperature ≤ the prevailing dew point. Mould, microbial, and house dust mite growth often result from this (CIBSE, 2005). In colder climates such as those typical in Northern Europe, buildings where no humidification equipment is installed can experience prolonged periods where indoor *RH* falls below the recommended lower value of 40%*RH*. This happens because the ability of air to hold water vapour decreases commensurate with declining air temperature. Resultantly, as cold ventilation air is heated to indoor temperature, its enhanced ability to retain water vapour means that its *RH* decreases proportionately.

Mechanical humidification equipment (MHE) can help counter this situation, but in most European Union countries, indoor %*RH* levels are not defined in statute so (due to financial implications), most buildings do not make use of such. That is, mechanical humidification is typically controlled by the heating and injection of steam into supply air (CIBSE, 2005); which calls for significant MHE capital outlay and high running costs. Humidification also has a negative impact on a building's carbon 'footprint' because for each 10 kg/hr of water vapour produced, circa 7.22kWh of gas is consumed as fuel, producing 1.61 kgCO_2 (Department for Environment Food and Rural Affairs, 2015).

IAQ is also a function of indoor carbon dioxide (CO_2) concentration levels (Lee *et al.*, 2002). Humans exhale CO_2 so indoor spaces are characterised by higher concentrations of CO_2 than are found in outdoor air. Usha *et al.* (2012) reported that high CO_2 concentrations are associated with poor IAQ and, that this could lead to health issues such as headaches, mucosal irritations, slower work performance, and increased employee absence. For this reason, CIBSE (2006) recommended a fresh air supply in the range of 5–8 litres per second per occupant, the aim being to sustain an internal CO_2 concentration in the range of 1,000 to 1,350 ppm.

Other pollutants affect IAQ, including certain building materials, furnishings, and equipment – the most pertinent of which are classified as VOCs. Zuraimi *et al.* (2006) confirmed that indoor VOC levels are typically higher than outdoor levels. VOCs can negatively affect occupants' health by increasing the occurrence of cutaneous and mucous membrane symptoms associated with sick building syndrome (Ekberg, 1994). The World Health Organisation (2010) recommends that indoor levels of formaldehyde and total VOCs should be lower than 100 and 300μg/m^3 respectively.

2.1 Indoor plants in office buildings

The ability of indoor plants to counteract indoor air polluting chemicals was first evidenced in the early 1980s and much of this research was undertaken by NASA (Wolverton *et al.*, 1989). Experiments found that soil acts as a sink for removing airborne VOCs such as formaldehyde (Wolverton and McDonald, 1982; Wolverton *et al.*, 1984) and benzene and carbon monoxide from closed experimental chambers (Wolverton, 1986). These studies also reported a significant reduction in air pollution, from within a modular structure that replicated an energy-efficient building. It was found that both plant leaves and their roots help in the air purification process (Wolverton, 1988).

Godish and Guindon (1989) built on these early studies, and examined the removal capabilities of plants under dynamic conditions where formaldehyde was continuously generated and released with varying emission rates. They found formaldehyde reduction rates of between 29-50%. Wolverton and Wolverton (1996) later showed how different plants grown in the same soil had significantly different formaldehyde removal abilities. Plants that culture large numbers of gram-negative bacteria (such as Pseudomonas) on or around their roots, are more effective at VOC removal than those that culture predominantly gram-positive bacteria. Giese *et al.* (1994), added support to the idea of air decontamination by plants. In their study, spider plants were put in contact with formaldehyde over a 24-hour period and this was removed by the plants to below detection limits, from the atmosphere of an experimental glass chamber within five hours. They suggested that a single 300g spider plant (*Chlorophytum comosum*) could 'detoxify' a $100m^3$ room in six hours. Another study indicated that efficacy of purification increased with greater numbers of plants, and that purification took longer with increasing molecular weight of the chemical being absorbed (Oyabu *et al.*, 2003).

Recent experimental work has considered the uptake rates of various plant species concerning specific VOCs, finding for example, that *Dracaena sanderiana* is highly efficient at Benzene removal (Treesubsuntorn and Thiravetyan, 2012). Of 12 species tested, *Sansevieria trifasciata* had the highest toluene removal rate, while the highest ethylbenzene removal rate was by *Chlorophytum comosum* (Sriprapat et al., 2014). Evidence based on test chamber experiments have also shown that at light CO_2 intensities (as commonly found indoors), hydroculture plants are more effective at CO_2 reduction than those grown in a traditional potting mix (Irga et al., 2013). (Hydroculture is where plants are grown in a static closed container system, containing an inert growth medium such as perlite or expanded clay, and saturated with a controlled nutrient solution). However, the rate of hydroculture VOC removal was found to be slower than for traditional potting mix plants. This study also highlighted the need to expand these kind of chamber experiments, to real indoor spaces (Irga et al., 2013).

Living plants such as Rhapis palms and Marantas (which require regular misting) or plants with a high moisture content, can benefit offices with sustained levels of low indoor air humidity (Costa and James, 1995). Such plants can increase the *RH* of a non-air-conditioned building by about 5%, although the planting density required to achieve this, would be higher than 'normally' provided for a commercial office environment (*ibid*.). Wolverton and Wolverton (1996) suggested that due to transpiration, plants may be used instead of (or as a complement to) mechanical humidifiers to supplement humidity levels in homes and offices. During photosynthesis, plants absorb CO_2 from the atmosphere through their stomata (tiny openings on the leaves), while the roots absorb moisture from the soil. Chlorophyll and other tissue in the leaves absorb radiant energy from light sources, which is used to split water molecules into oxygen and hydrogen. Plants use the hydrogen and CO_2 to form sugars while oxygen, a by-product of photosynthesis, is released into the atmosphere (Wolverton, 1986).

Smith *et al.* (2011) reported a plant trial in an open plan office where short-term sickness absence was reduced in the planted experimental area, by approximately half of that in a control area. A saving of circa £40,000 GBP per annum was reported as a result of this. However, they acknowledged that results were limited to one building and one small sample, recommending further research in this area. Especially, given an apparent dearth of literature on indoor planting and workers' sickness absence.

Evidence also suggests that indoor plants can help reduce ambient noise levels, although it is unlikely they would act as efficiently as dedicated sound attenuation construction solutions.

Costa and James (1995) contended that plants might achieve acoustic quieting by absorption; as did Freeman (2008) who suggested plants may absorb, diffract, and reflect sound dependent upon their characteristics; such as size, shape, container, top dressing, compost, and positioning. Indeed, indoor planting density commensurately increases noise reduction efficacy (Costa and James, 1995). Considerable environmental psychology research has studied the role of nature. For example, outdoor natural environments and vegetation have been shown to provide several psychological benefits including positive feelings (Sheets and Manzer, 1991), environmental awareness (Lutz *et al.*, 1999), reduced driver frustration (Cackowski and Nasar, 2003), reduced crime (Kuo and Sullivan, 2001) and enhanced cognitive functioning in children (Wells, 2000).

While 'completely natural' office building environments may not be fully achievable, research confirms that natural environment views from windows can provide restorative effects, from mental fatigue (Kaplan, 1993) and job stress (Leather *et al.*, 1998). Bringslimark *et al.* (2011) assessed whether office workers compensate for a lack of natural views and found that those in windowless offices were approximately five times more likely to bring plants into their workplace. Indoor plants at work have also been associated with improved attentiveness (Lohr *et al.*, 1996), better task performance (Shibata and Suzuki, 2001) and a reduction of sick building syndrome symptoms (Gou and Lau, 2012). Additionally, active interaction with indoor plants can reduce physiological and psychological stress (Lee *et al.*, 2015).

3. Methodology

A mixed-methods study was used that employed theoretical humidity and power consumption analysis, physical data logging, and a perception questionnaire survey. This methodology is described in terms of: i) the building, ii) theoretical design; iii) planting arrangements; iv) relative humidity; and v) employee perceptions.

3.1 The case study building

The building was a Local Council Head Office in Southern England, responsible for a population of c.270,000 people and a land area of 5,400ha (c.208 square miles). It was constructed in 2011 and comprises three storeys, with a gross floor area (GFA) of 10,300m^2 of office space arranged predominantly in an open floor design, surrounding a central atrium. The main entrance is located at ground floor level (Figure 1).

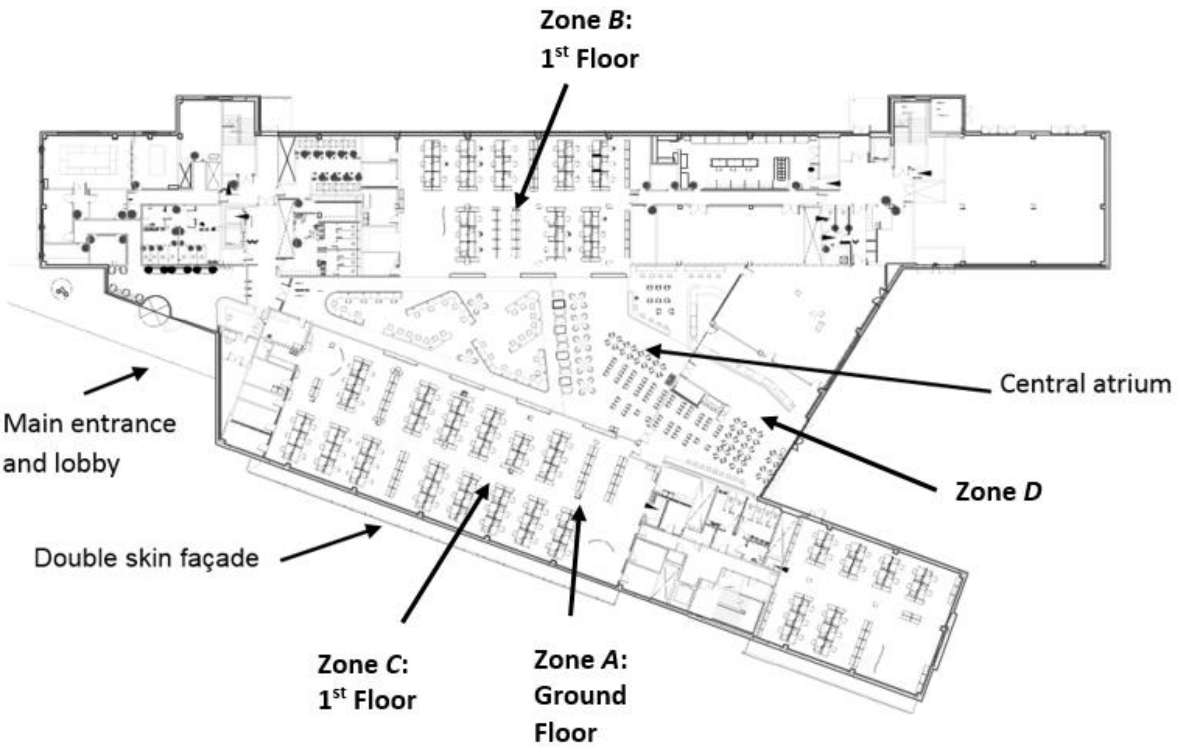


Figure 1. Plan design schematic for the ground floor

The building has an energy performance operational rating of 'C' (Department for Communities and Local Government, 2015) with an annual gas and electricity consumption of 73 and 72 kWh/m^{2}GFA/annum respectively. Approximately, 13% of the former and 0.4% of the latter is sourced from renewable energy. Gas is the main heating fuel, while electricity is used for lighting and all other power requirements typical of an office building. Building services are fully linked to a central Building Management System, which controls lighting, ventilation, heating, and the opening and closing of apertures. The building design allows a high percentage of ventilation to be achieved via natural 'stack effect' through the atrium. Strategically located CO_2 sensors monitor IAQ with the mean indoor CO_2 concentration maintained at circa 850ppm. For this study, supplemental CO_2 readings were recorded with a handheld Solomat MP Surveyor PRO, Zwellweger Analytics CO_2 sensor. Similarly, indoor lighting and noise levels were recorded with a handheld PeakTech 5035 sensor. These sensors were calibrated by their respective suppliers prior to the commencement of the study.

A central HVAC system, located on the rooftop, provides heating and supplemental ventilation through floor level diffusers with winter and summer indoor point temperatures set at 22^{o}C. No cooling or humidification systems are available. Figure 2 shows the central atrium and double skin south facing façade. The façade offers sound insulation from a high-volume traffic road parallel to it, as well as shading, to minimise solar gains during peak summer months. At the time of the study there were circa 1,000 adults working in the building, typically between the hours of 8am and 7pm. As illustrated in Figure 1, a single experimental zone (Zone A) and two control zones (Zones B&C) were designated. The number of employees and moisture buffering from surface finishes and furniture in each zone was assumed to be identical. Moreover, with the staff canteen and toilets (Zone D) abutting on the atrium, the exposure of each zone to moisture originating from these locations was assumed to be equal.

2 (a) Atrium design 2 (b) South facing façade

Figure 2. The office building

3.2 Theoretical calculations of mechanical humidification

The water vapour per unit volume of dry air required for the elevation of the indoor %*RH* to the lower recommended limit of 40%*RH*, was calculated using a psychrometric chart, based on measured indoor air temperature and %*RH* readings. Subsequently, the total mass of water vapour per unit time (kg/hr), required as a function of the building occupants and the mean fresh air ventilation rate, was derived from:

$$\dot{m}_m = m(3.6\rho_{air} n v_{fa}) \tag{1}$$

where: m is the mass of water vapour per kg of dry air; ρ_{air} is density of air (kg/m^3); n is the number of employees; v_{fa} is the fresh air volume flow rate (L/s) (CIBSE, 2005). A fresh air ventilation rate of 8L/s was assumed, which would yield an indoor CO_2 concentration of circa 1,000 ppm (CIBSE, 2006). The heating power required to heat fresh water from an assumed 20^{o}C to boiling point, was calculated using:

$$Q_w = \dot{m}_m C_p \Delta T \qquad \textbf{(2)}$$

where: Q_w is the heating power (W); $\dot{m}_m$ is the mass of water required per hour calculated from equation (1); C_p is the specific heat capacity of water (J/kgK); and ΔT is the change in water temperature (i.e. from 20°C to 100°C). The heating power required to evaporate water at 1Bar was calculated from:

$$Q_{st} = \dot{m}_m \Delta H_{vap} \qquad \textbf{(3)}$$

where: ΔH_{vap} is the enthalpy of vapourisation (kJ/kg). Hence, the total power (Q_{tot}) required for the production of steam was calculated from addition of equations (2) and (3). That is:

$$Q_{tot} = Q_w + Q_{st} \qquad \textbf{(4)}$$

Using a mean daily operating time of 11 hours, the energy required for production of steam per month was derived from:

$$E = \frac{Q_{tot} t}{1000} \qquad \textbf{(5)}$$

where: E is the energy consumed (kWh) and t is time (hrs). The predicted energy saving per month as a result of water vapour contribution from the indoor plants, was calculated from:

$$E_{sav} = \left[\frac{\dot{m}_{pl}}{\dot{m}_m}\right] E \qquad \textbf{(6)}$$

where $\dot{m}_{pl}$ is the mass of water vapour transpired by the plants per unit time (kg/hr).

Hence, equation (6) was used to quantify the tangible benefits of using indoor plants to supplement the indoor *RH*. As discussed later, these gains take the form of financial savings and environmental benefits, as a result of reduced gas consumption.

3.3 Planting arrangements

Live indoor plants were installed in the building among the first floor southern section of the building (refer Figure 1) for a period of 6 months. These areas were chosen because they are of similar size and are occupied by approximately the same number of people, doing similar jobs (Smith *et al*., 2011). The plants were selected mainly for their transpiration rates according to Wolverton (1996) as well as factors such as: ease of maintenance, light requirements, size, shape and general aesthetic qualities (Smith *et al.*, 2011). This was all in accordance with the advice of a professional indoor planting company, who also supplied and carefully maintained the plants throughout the trial period. Maintenance is important because plants must be in optimal condition, for them to be successful in regulating indoor climate (Costa and James, 1995; Smith and Pitt, 2011) – this included watering (volumes recorded), dusting, and pest control (using natural products) every 2 weeks.

The plants are detailed in Table 1. They were installed at a density of one plant per 10m^2, a density slightly higher than under 'normal' commercial conditions. They included 30 floor-standing varieties and a range of 24 smaller desk bowls, mainly positioned on shared furniture, such as filing cabinets. The plants were all soil-grown and without top dressing. In line with the planting company's advice, the total transpiration for the experimental zone was calculated to be approximately 21 litres of water per 24 hours.

[Insert Table 1 here].

Table 1. Plant species installed in the experimental zone

3.4 Relative humidity

Two newly calibrated column-mounted HOBO UX100-003 humidity sensors (accuracy +/- 3.5%) were mounted in each zone (six sensors in total); at a height of circa 1.6 m above floor level on support columns located in the central part of the monitored zones. Their readings were automatically logged at half-hourly intervals and resulting ratios of actual water vapour density to the saturation vapour density were calculated from:

$$\%RH = \frac{\rho_{actual}}{\rho_{saturation}} \tag{7}$$

Figure 3 shows that saturation vapour density is directly related to air temperature, such that a unit increase in air temperature results in an exponential rise in its ability to hold water vapour. Hence, if supplemental water vapour is not added to heated indoor air, its *%RH* decreases appreciably. Testing for VOCs used ISO 16000-4-2004 standard formaldehyde and Total VOC testing kits. Two samples were logged for each of the three zones, with the first sample taken during February and the final sample taken during June.

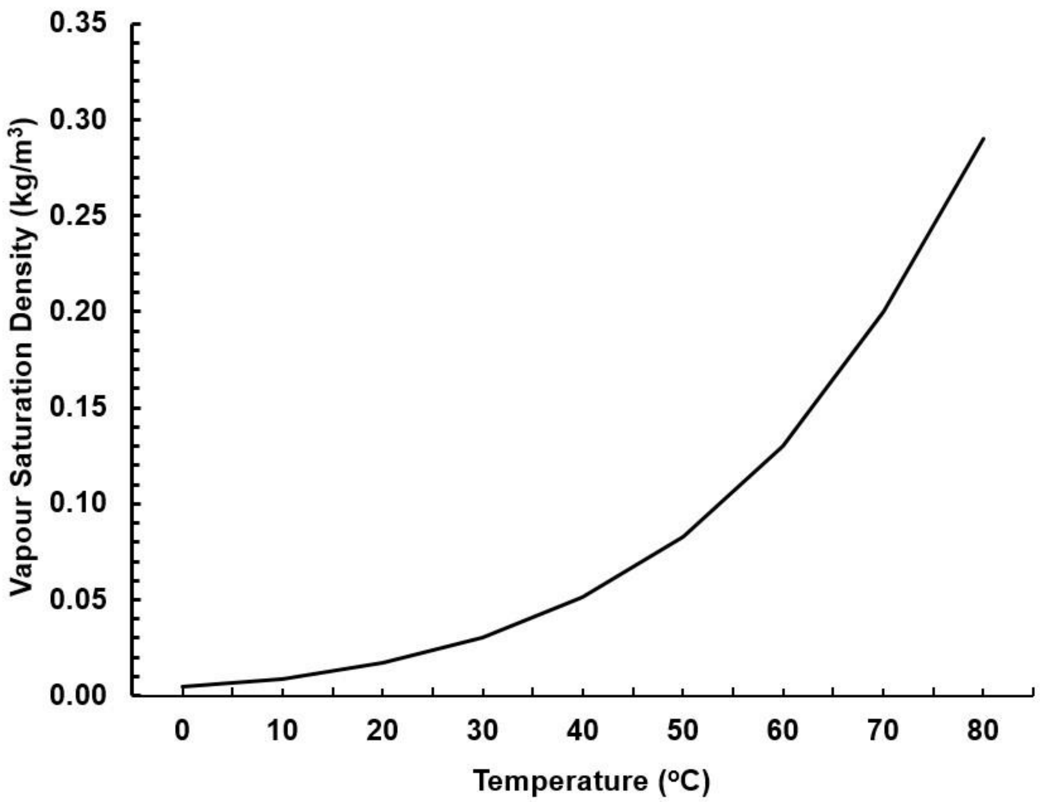


Figure 3. Vapour saturation density with temperature

The water vapour volume that evaporated from the 54 indoor plants was calculated from:

$$\dot{m}_{pl} = TR(n_{pl}A) \qquad \textbf{(8)}$$

where: *TR* is the mean transpiration rate of 0.0218 kg/hr/m^2 (Hussarang *et al.*, 2011); n_{pl} is the number of plants; and *A* is a mean foliage area of 0.906m^2 per plant (*ibid*.). By way of checking, the total water vapour volume mass produced, was compared to that of water supplied to the plants over the duration of the project. The outcome was validated with the supply value being +/-10% of $\dot{m}_{pl}$.

3.5 Employee perceptions

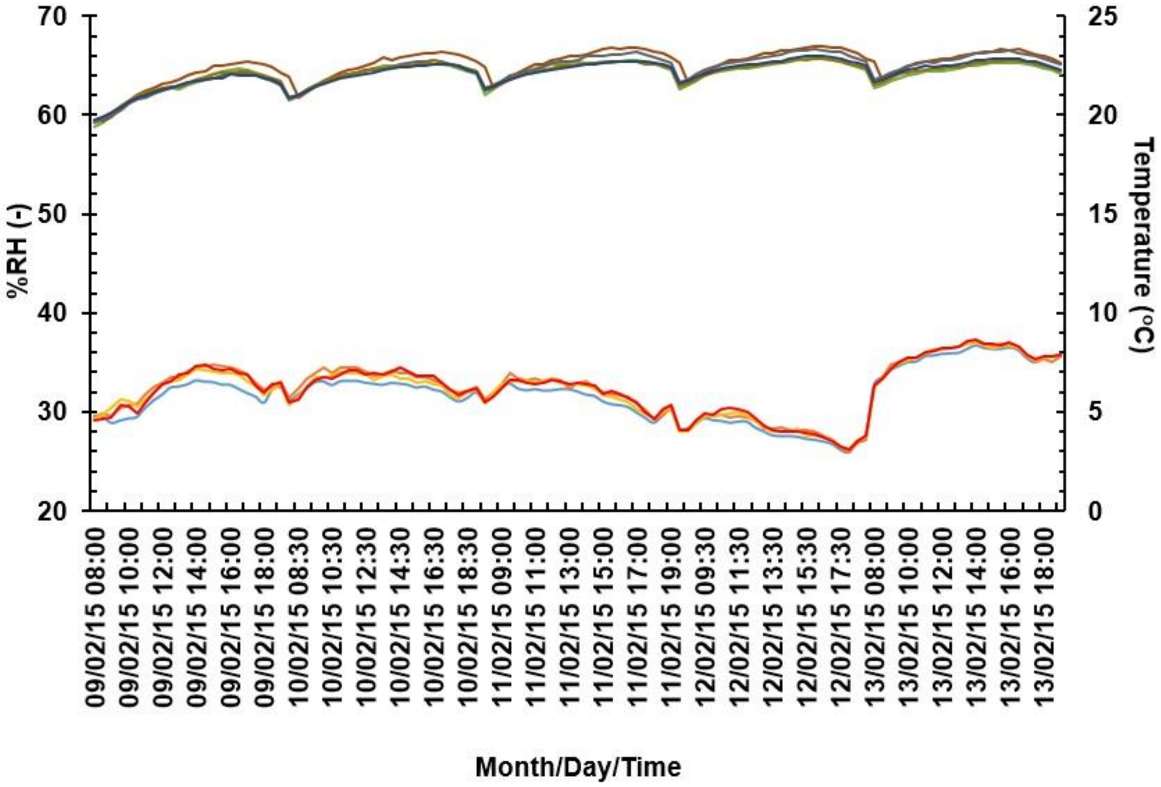
During the last two weeks of the trial period (June 2015), employees' perceptions of their working environment were sampled among both the 'trial' and 'control' zones, using an online questionnaire. This method was chosen for ease of distribution (Heiervang and Goodman, 2009); efficiency (Hardigan *et al.*, 2012); and convenient data export (Archer, 2003). It also encouraged employees, to complete the survey via their desk terminal while within the survey (work) environment. The questionnaire asked employees to consider whether any of four environmental aspects had 'improved', 'stayed the same', or 'got worse' since the plant trial had commenced. These aspects were: humidity; temperature; background noise levels; and environment aesthetics.

Among the control zones there were 61 (55%) respondents. The remainder (n = 49, or 45%) of the sample were from the trial zone. The total 110 respondents formed a reliable sample given their proportion of the original population, and because where n>30 normality can be tentatively assumed – even more so, as n increases thereafter (Mordkoff, 2011). Data were analysed using real numbers and percentages, to create graphical categorical comparisons – methods appropriate for interpretation of results among nominal or interval data (Holt, 2014).

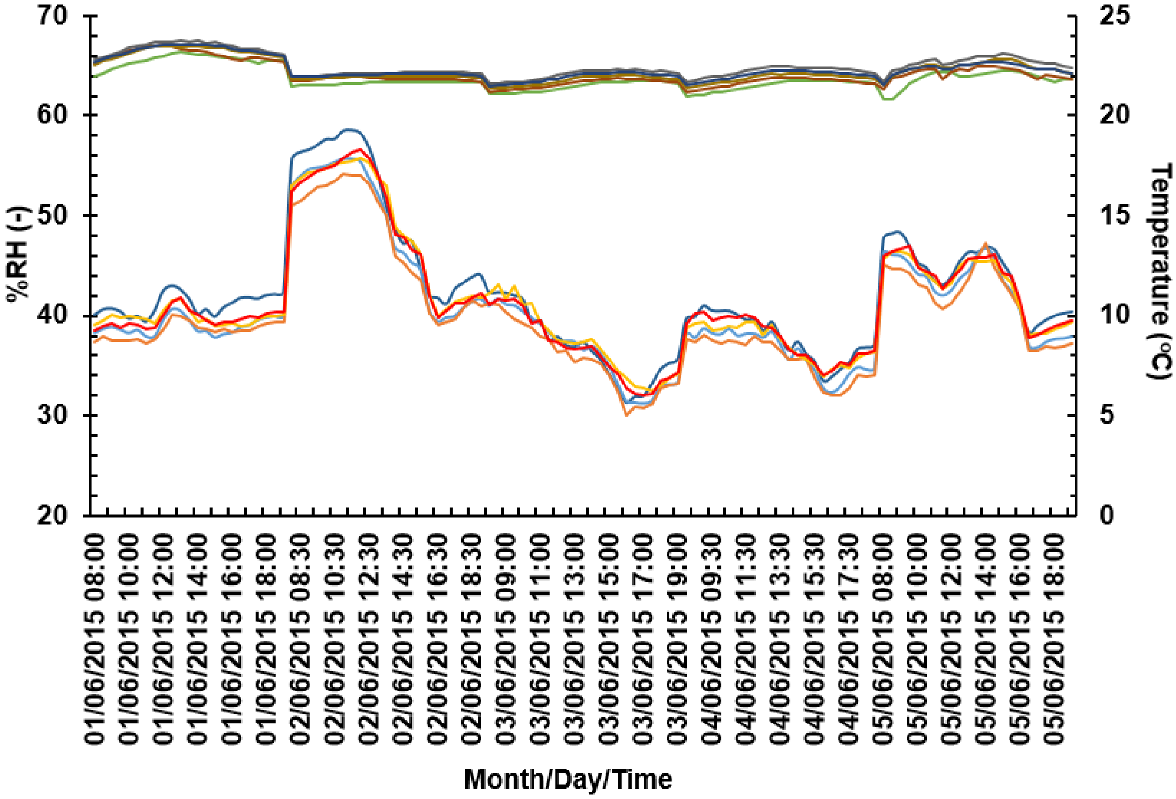
4. Results and discussion

Figure 4 shows the %*RH* and indoor temperatures during a week in February (a) and another in June (b). In contrast to expectations, the %*RH* in the experimental zone was quasi-identical to those in the control zones. Moreover, the data suggest that the %*RH* (in all zones) is highest during the late morning/early afternoon, which may be attributed to the peak number of employees in the building at about this time.

Figure 5 presents the average measured external temperature, internal temperatures and %*RH* (combined for all zones) over the trial period. In agreement with concerns reported by the building's facilities management, indoor %*RH* during the months of January to April was below the recommended CIBSE minimum of 40% (CIBSE, 2005; Wan *et al.*, 2009). The lowest indoor *RH* levels were recorded during February while the highest levels were recorded during late spring months. These results can be directly associated with corresponding outdoor temperatures. For example, during February outside cold air contained much less water vapour at saturation conditions, so the heating of this air to room temperature yielded a significant drop in indoor *RH*.



4 (a) February



4 (b) June

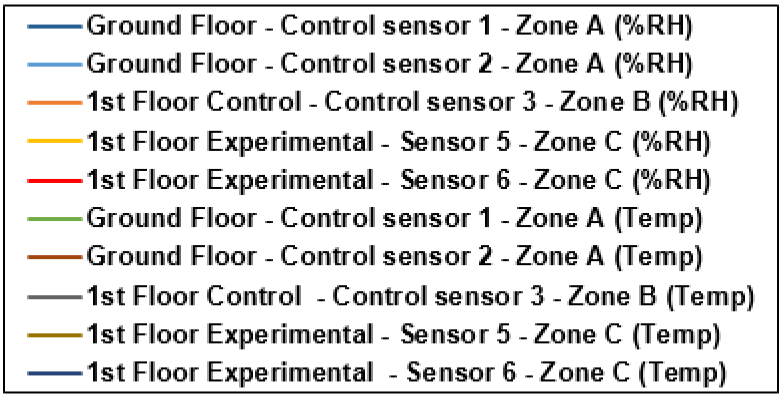


Figure 4. ***%RH*** **and indoor temperature with time (office hours) during a week in February (a) and June (b)**

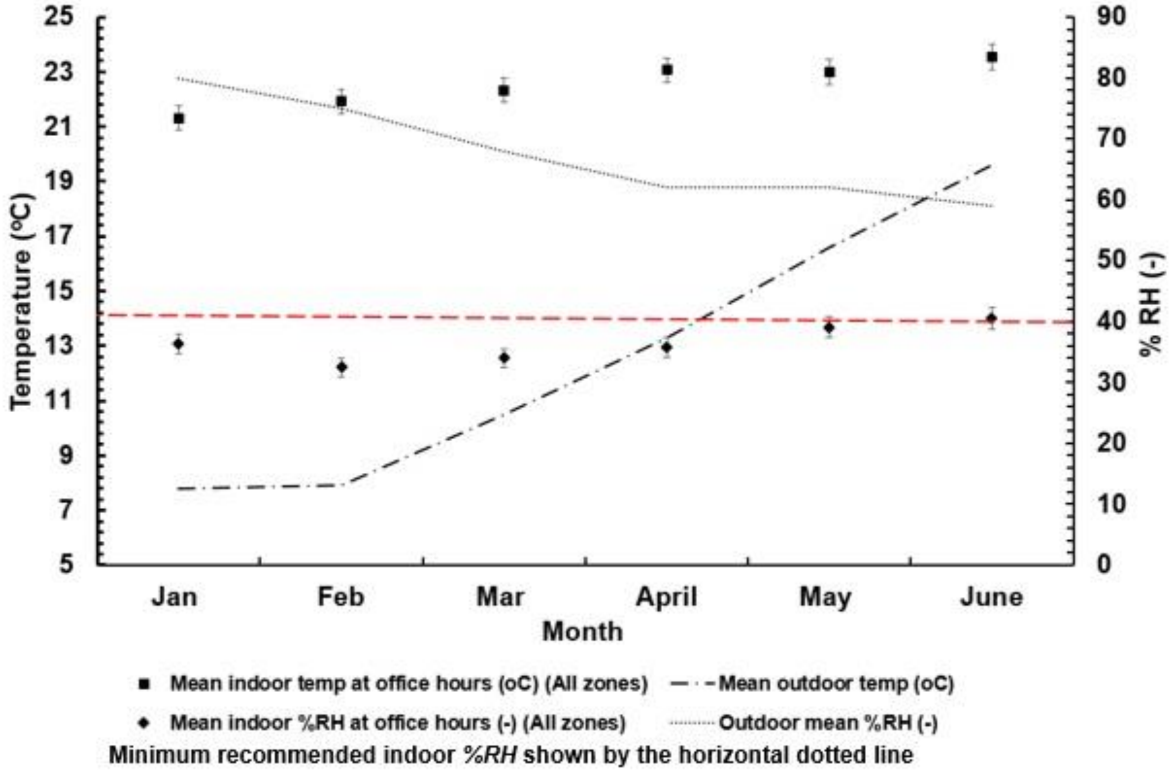


Figure 5. Average measured indoor temperatures, outdoor temperatures and *%RH*

Indoor %*RH* values for the experimental and control zones were quasi-identical, and so are grouped together in Figure 5. These findings contrast a-priori expectations – given that a total volume of 3,822 litres of water were supplied to the plants during the six month trial period. Moreover, with a total foliage area of circa 49m^2, a mean transpiration rate of circa 18g/hr/m^2 was calculated [in reasonable agreement with the transpiration rate of 21.8g/hr/m^2 reported by Hassarang *et al.* (2011)]. Figure 6 shows how these transpiration rates were expected to significantly reduce mechanical humidification energy demands. For a sustained indoor 40%*RH*, mechanical humidification with no indoor plants, was calculated to increase gas consumption by 7%. Hence, during January and February, the plants were predicted to reduce mechanical humidification energy by 75 and 38 per cent respectively (a saving of circa 6,000 kWh over the period). For the trial period, a total CO_2 reduction of 2,200kg (Figure 7) was calculated (Department for Environment Food and Rural Affairs, 2015).

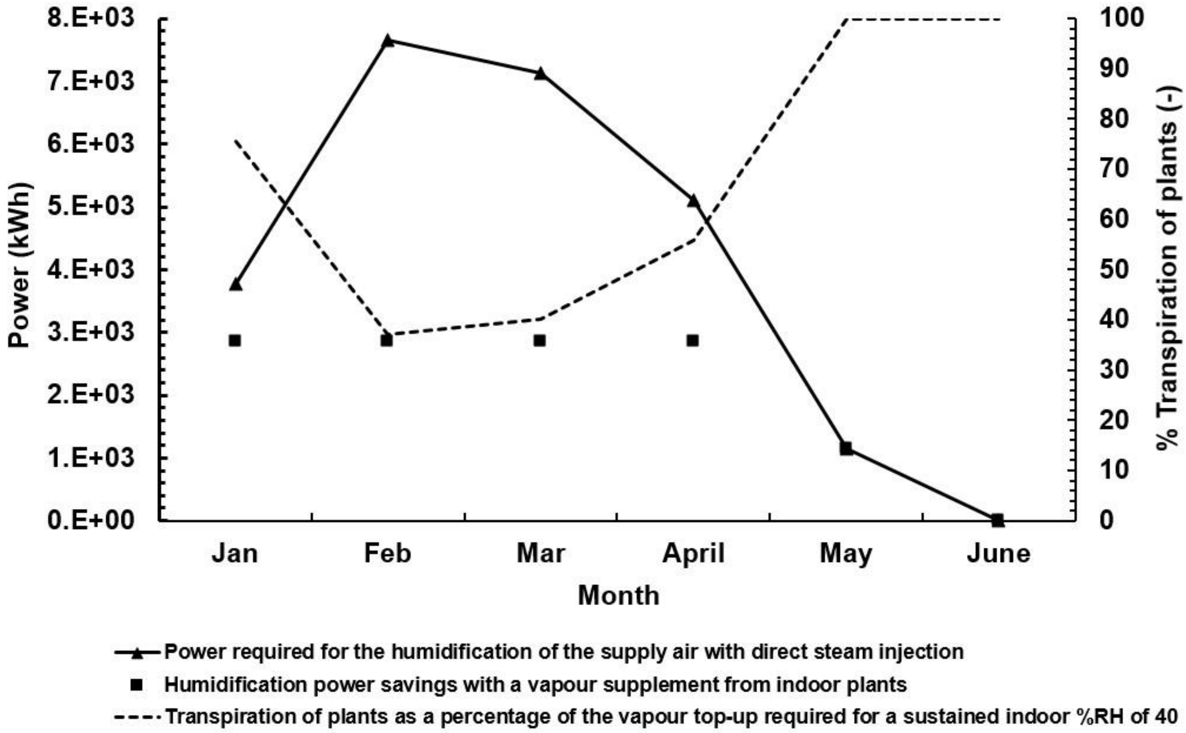


Figure 6. Theoretical power consumption with indoor air-humidification provision and potential power savings with a vapour supplement from indoor plants

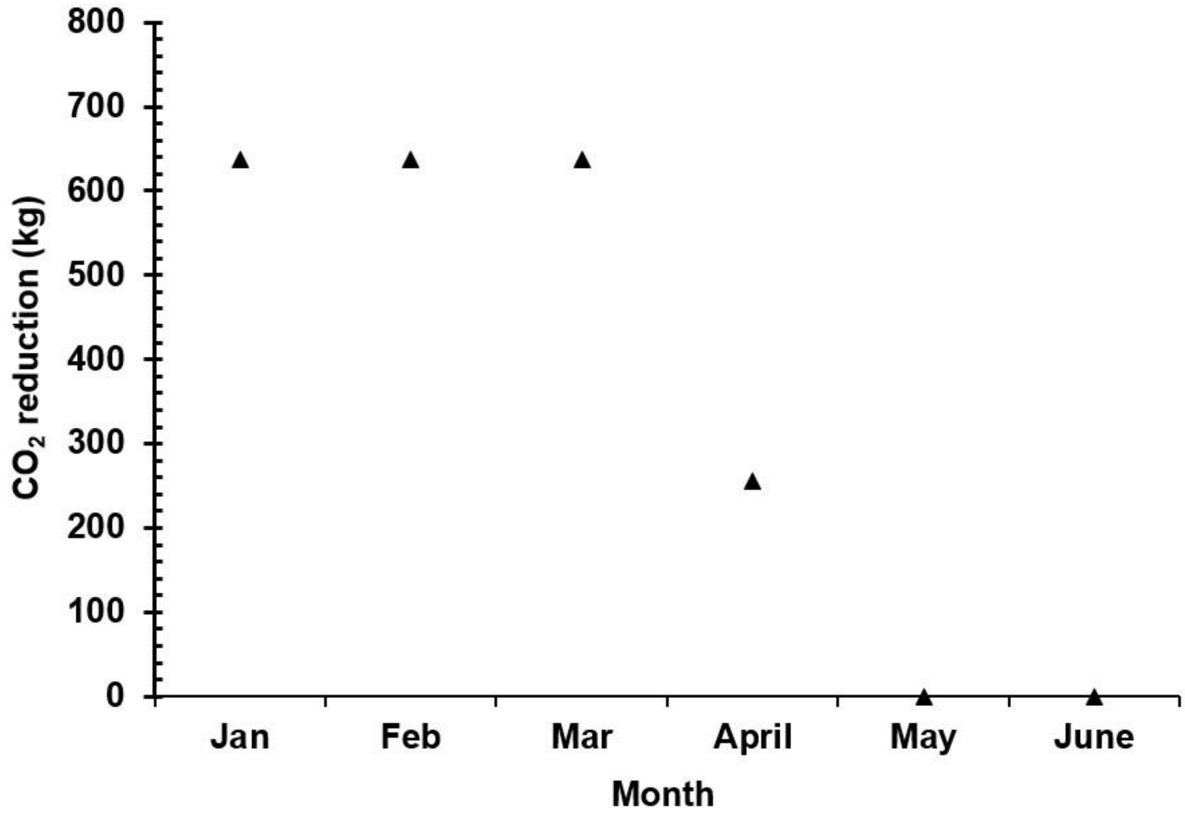


Figure 7. Theoretical CO2 gas reduction with indoor plants

The marked differences between measured and predicted %*RH* may be attributed to building design, which it is assumed, allowed cross-contamination of indoor air between the experimental and control zones. It is logical to infer that this resulted in some dilution of the concentration of water vapour, transpired by the plants located in the experimental zone. A corollary of this suggests it will be necessary to populate all of the building's indoor areas with plants, to achieve enhanced indoor humidity levels. Moreover, indoor CO_2 gas concentration data suggest that results were not attributable to over-ventilation. Recorded mean indoor CO_2 concentration was in the range of 850-1000ppm, this being indicative of good IAQ (Usha *et al.*, 2012). This suggests an approximate ventilation rate of 8-10 L/s per person (CIBSE, 2006).

Figure 8 shows the measured concentrations for TOTAL VOCs (TVOCs) and formaldehyde, at µg/m^3 among the control and experimental areas. Both sets of data show concentrations much lower than the recommended maximum of 100 and 300 µg/m^3 for formaldehyde and TVOCs respectively (World Health Organisation, 2010). This additionally suggests no substantial differences in the concentrations of experimental vis-à-vis control zones. However, it is evident that during June, the TVOC concentrations were consistently lower than during January. Given that formaldehyde concentration and CO_2 readings were consistent for both months, these results do not appear due to higher ventilation rates, and so remain indeterminate.

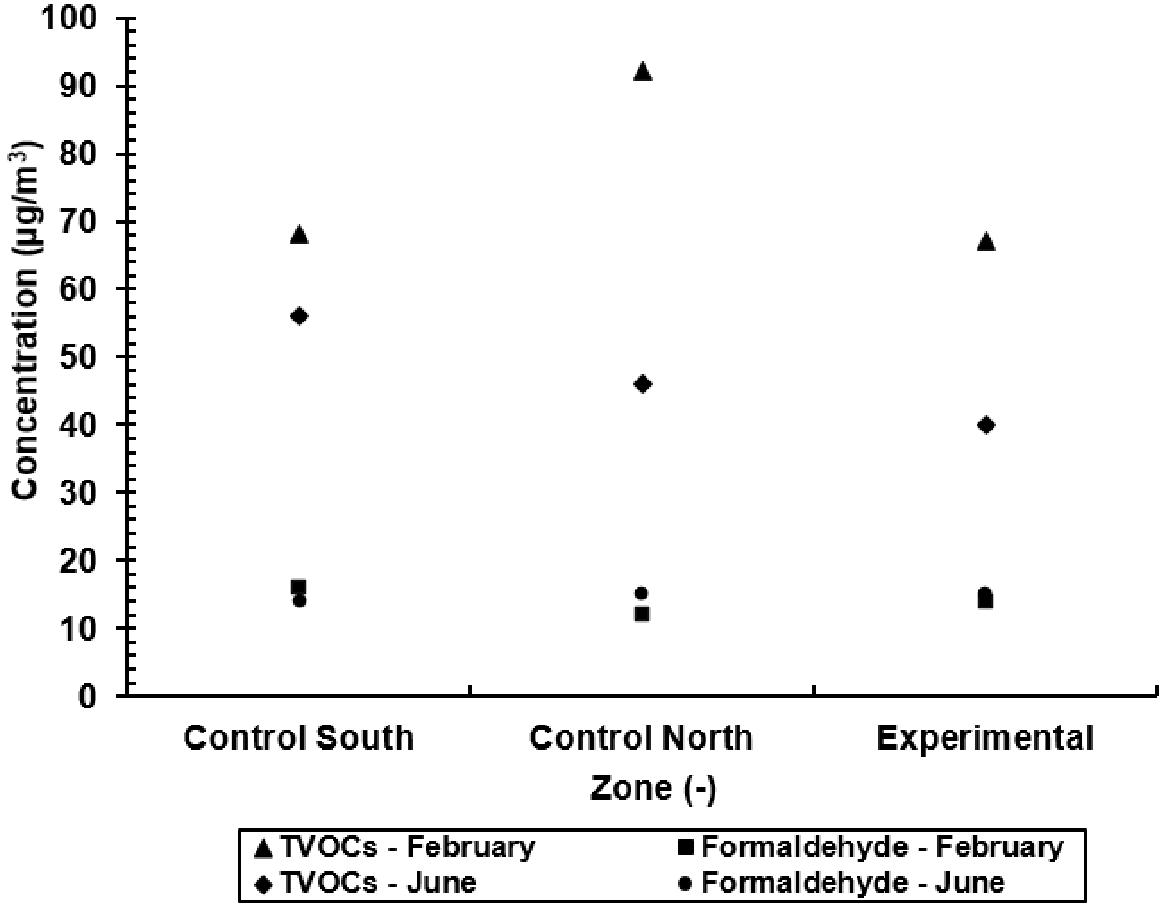
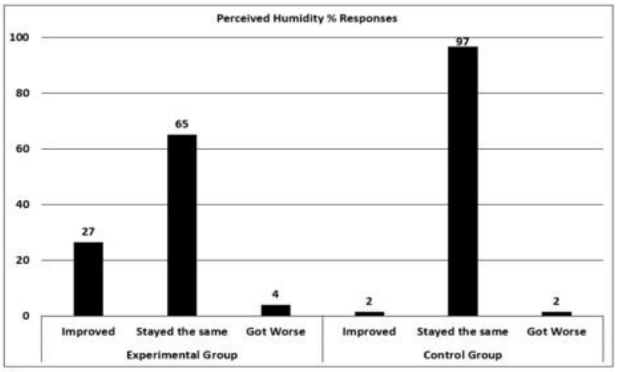
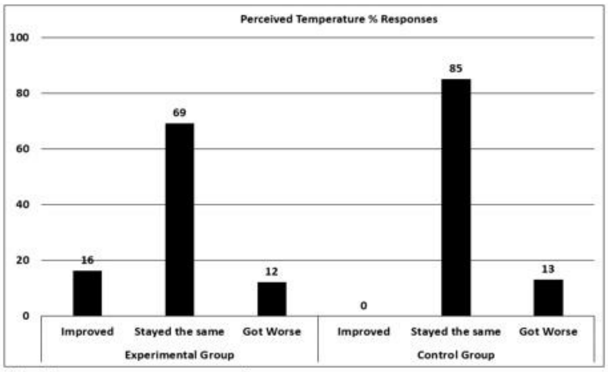


Figure 8. VOC measurements for the experimental and control zones

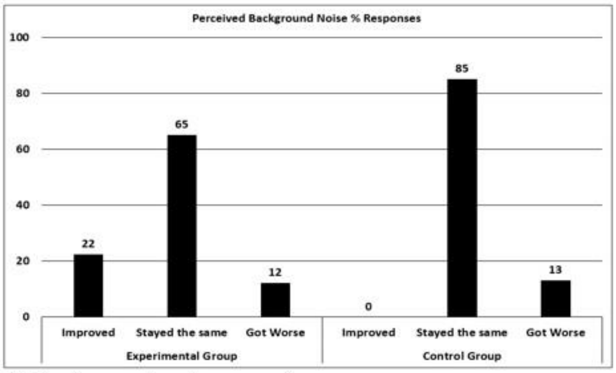
The questionnaire survey found a noticeable shift in perceptions within the experimental zone; approximately one-quarter of respondents felt that indoor *RH* had improved. This contradicts actual *RH* measurements and so suggests a misperception. While beyond the remit of this study, reasons for misperception include distortion from an array of cognitive, perceptual and motivational biases [reasoning error; experientially influenced perception; and personal or situational leanings, respectively (Pronin, 2007)]. In this instance, maybe from optimism bias, which is the tendency to underestimate the likelihood of being affected by adverse events or conditions (Moss, 2016); or acquiescence bias, which is the tendency to respond affirmatively to survey items irrespective of substantive content (Watson, 1992). Notably, almost all respondents from the control groups felt that *RH* had not changed. Figure 9(a) shows all results between both groups in terms of *RH* perceptions. A similar condition was reported regarding temperature, with almost one-third of experimental zone respondents perceiving change in temperature, which again contradicts actual temperature readings. The majority of respondents in all areas perceived that temperature remained the same (Figure 9(b)).



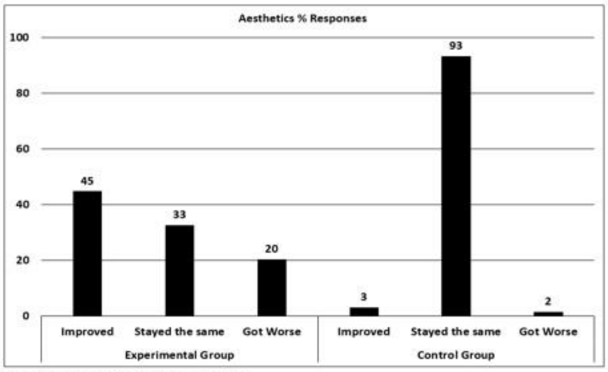
(a) Humidity perceptions



(b) Temperature perceptions



(c) Background noise perceptions



(d) Aesthetic perceptions

Figure 9. Results of the questionnaire survey

In accordance with research by Costa and James (1995) and Freeman (2008), the questionnaire results suggest a perceived improvement in background noise levels, within the experimental area. Although this contradicts physical measurements (mean noise levels of 45-55dB were measured among all zones), it may provide an indication of the sound absorption properties of plants in buildings (or a reduction in reverberation times that was perceived as reduction in noise). Twenty-two per cent of experimental area respondents reported this improvement, compared to none in the control areas (Figure 9(c)).

The most marked perceived improvement was for aesthetics within the experimental area. Figure 9(d) shows that almost half of respondents reported this, although one-fifth of experimental area respondents suggested that aesthetics got worse. This reflects the subjective nature of office design considerations and individuals' differing opinions as to the addition of indoor plants at work. Nonetheless, these results concur with Smith and Pitt (2008) who found a general preference for plants in this context.

5. Conclusions

The study has presented a mix of numerical and qualitative investigations regarding the impact of living plants on IAQ. The measured indoor *RH* suggests that despite what theoretical calculations predicted, in practice the humidification effect of the plants was not discernible. The research team feel that this is mainly due to the open plan design of the building, which allowed cross-contamination of air between those zones studied. The volume of water supplied to the plants over the investigation period, together with calculations of their typical transpiration rates based on the literature, suggests that during winter months, indoor plants offer the potential to reduce mechanical humidification power requirements by up to 75%. These savings were calculated based on a minimum indoor *RH* of 40% (a comfortable and healthy indoor environment for the building's occupants).

Changes in perception were shown to contrast those physical data measured in relation to indoor *RH*, temperature, and background noise levels. This misperception probably results from optimism or acquiescence bias, and suggests that future perception surveys of indoor planting need to account for this, in questionnaire design. The most marked improvement related to aesthetics in the experimental zone where the plants were located, supporting an argument that office occupants appreciate the presence of natural elements such as plants.

This research suggests that analysis of airflow patterns within the building using computational fluid dynamics would be beneficial, in order to study the degree to which inter-zone mixing of air can affect positive *RH* gains from indoor planting. Linked to this, future work will also assess the effect of indoor planting throughout *all* of the building. This in addition, will further knowledge of zonal air interfaces in the present context; and equally compare occupants' perceptions of those indoor environmental criteria used in the present study.

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