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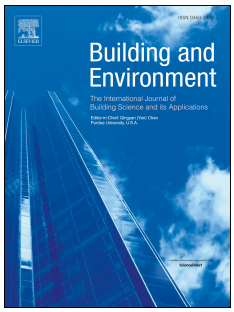

Indoor air pollutants in occupational buildings in a sub-tropical climate: Comparison among ventilation types

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Indoor air pollutants in occupational buildings in a sub-tropical climate: Comparison among ventilation types.

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Keywords:

Particulate matter,

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Highlights:

Several air pollutants were assessed in eleven buildings throughout one year

Air pollutants in natural, mechanical and mixed-type system ventilation were compared

Low concentrations of airborne fungi were encountered across all buildings and months

Naturally ventilated buildings had higher concentrations of fungi

No air pollutants observed presented an occupant health risk

Abstract

Few studies have concurrently assessed both abiotic and biotic air pollutants in the built environment in sub-tropical areas. The investigation comprised a field study of air pollutants in eleven indoor environments in Sydney throughout one year, to elucidate Indoor/Outdoor ratios of carbon dioxide, carbon monoxide, total volatile organic compounds, nitric oxide, nitrogen dioxide, sulfur dioxide, total suspended particulate matter, suspended particles <10 μm in diameter (PM_{10}) and particulate matter <2.5 μm ($PM_{2.5}$). Further, a concurrent assessment of airborne fungi was conducted along with the other air pollutants to determine their diversity and abundance for urban Sydney and to establish baseline Indoor/Outdoor ratios of airborne fungi. Building ventilation types were identified as natural, mechanical and mixed-type ventilation, to assess whether building ventilation type has an impact on prevalence and concentrations of indoor air pollutants. We found that generally the indoor air quality of a typical Australian office building is relatively good. The ventilation type of the buildings did affect indoor air quality; however not to the extent that occupant health was at risk in any case. Low concentrations of airborne fungi were encountered in samples, across all buildings and months, with naturally ventilated buildings having higher concentrations. Buildings with high airborne fungal concentrations also supported higher diversity of fungal species. Few organisms of concern to public health were identified. Significant differences were observed when comparing the structure of airborne fungal communities across

building types, with buildings with centralised mechanical (air conditioning) systems harbouring different communities to the other ventilation types.

1. Introduction

Indoor environmental quality and especially indoor air pollutants are a growing concern, as populations become more urbanised, and an increasing majority of individuals spend most of their time in indoor environments. Therefore, knowledge about the composition, sources, health effects and methods for the reduction of indoor air pollutants is becoming increasingly important. The accumulation of, and continued exposure to, indoor air pollution may result in Sick Building Syndrome (SBS). SBS describes situations in which building occupants experience acute or subacute health and discomfort effects that appear to be linked to the duration of time spent in a building [1], with the direct cause of the symptoms undefined, but are rapidly relieved after one has left the building. Typical SBS symptoms range from upper respiratory symptoms; to dermal symptoms; to tiredness and malaise [2].

Indoor air pollution can come from both the ambient outdoor air penetrating into indoor environments, and directly from indoor sources [3]. As is the case outdoors, indoor air pollution is generally comprised of a mixture of particulate matter (PM); carbon dioxide (CO_2); carbon monoxide (CO); nitrogen dioxide (NO_2); sulfur oxide (SO_2); volatile organic compounds (VOCs) and bioaerosols comprised of fungal propagules, bacteria, pollen and animal detritus [4]. Exposures to bioaerosols in the occupational environment is associated with a wide range of health effects that have a growing public health impact, including infectious diseases, acute toxic effects and allergies [5].

The concentration and composition of indoor air pollutants is determined by a number of factors, with the presence of a source of the individual pollutants and building ventilation system type (and rates) likely to be the predominant factors in most scenarios. The relationship between these two factors can be complicated, as the pollutant source component regularly changes temporally, as does the ventilation system effects due to thermal conditioning requirements that vary throughout the day and seasonally. Ventilation system type, therefore, can be a major determinant of the composition and concentration of indoor air pollutants, and can provide a valuable explanatory component when assessing indoor air pollution levels.

Three different ventilation system strategies are normally utilised in commercial and non-residential buildings. The first is *natural ventilation*, where windows, doors, skylights and roof ventilators are simply left open to the atmosphere. This method supplies an ample amount of air for buildings if there is sufficient open area and flow through, although this may not be the case for many buildings constructed in the last 20 years. Air from natural ventilation is not conditioned, and will permit the entry of all outside air contaminants down the concentration gradient, as well as permitting the diffusion of indoor-sourced pollutants to atmosphere. In Australia, this ventilation type is found in a restricted number of smaller commercial buildings, as well as in many schools, kindergartens etc.

The second is *mechanical ventilation*, by which the air is supplied, conditioned (humidity modified) and thermally regulated with the use of a Heating and Ventilating Air Conditioning systems (HVAC). Most of these buildings have no operable windows, with all fresh air passing through the mechanical system. Central HVAC

systems tend to be composed of an intake for outdoor air located on the roof or side of the building, a duct bringing outdoor air to an air treatment unit and vents at the ceiling for air circulation The air treatment unit filters, heats or cools, dehumidifies or humidifies the air and distributes it through a duct network to air vents throughout the occupied spaces of the building. In Australia, most buildings run at constant air volume, with 20% of the total volume of air delivered sourced from outdoor air and 80% is recirculated.

The third ventilation system type, and common in the Australian climate, is a *mixed model ventilation*, combining natural and mechanical ventilation system methods, usually through the use of window unit type air conditioners in high use or sensitive spaces, but with a substantial and highly variable natural ventilation component through opening windows and doors.

Although natural ventilation provides numerous benefits in areas within a moderate climate, the concentration of indoor airborne pollutants can be higher in naturally ventilated buildings in some circumstances, due to outdoor particles and gases being transported indoors through openings in the building envelope. Concentrations of indoor pollutants within naturally ventilated buildings are significantly influenced by the penetration of outdoor particles through the openings [6]. Few studies have compared quantitative measurements of indoor pollutant concentrations across different ventilation systems, especially for mixed model ventilation systems [7]. It is not well known how the different ventilation methods affect the concentrations of air pollutants within buildings, including in Sydney.

In Australia, ambient air pollution standards are set by *The National Environment Protection (Ambient Air quality) Measur*e (Air-NEPM) [8]. The standards used are similar to those from most western countries. The Air-NEPM standards cover most of the common air pollutants, including particulates less than 10 micrometres in size (PM_{10}), particulates less than 2.5 micrometres ($PM_{2.5}$), SO_2, NO_2, and CO. Australian threshold limits for indoor workspace CO_2 and volatile organic compounds (VOC) are set by Work Safe Australia [9]. Although Australia has standards or at least guidelines in place for most indoor air pollutants, no Australian law exists with respect to workplace fungal bioaerosol exposure, and no Australian recommendations currently exist for fungal concentrations detected in buildings. Occupational hygienists and air quality professionals commonly adopt the guidelines from the American Conference of Industrial Hygienists (Air Sampling Instruments for Evaluation of Atmospheric Contaminants, 1995) and the World Health Organization (WHO, 1988). However, these international recommendations may not be applicable for Australian meteorological conditions, climate, and fungal ecology (e.g. [10]). An additional inconsistency in the international recommendations is the lack of uniformity in how the regulations are presented. For example, some suggest that an acceptable measure could be the ratio between indoors and outdoors, while others suggest that indoor levels of total numbers and/or specific numbers exceeding a certain quantity should be investigated [11, 12]. The focus on individual species may be very important for pathogenic species which in some situations can be of serious concern for immuno-compromised individuals, and public health as a whole [13].

In a Sydney study by Torpy *et al*. [14], it was found that the fungal genera *Cladosporium*, *Penicillium* and *Alternaria* were the most frequently observed among indoor culturable fungi. Additionally, no seasonal differences were observed between autumn and spring samplings. With respect to outdoor culturable fungi in Sydney [10], the genera *Cladosporium* and *Alternaria*, were most frequently observed. Increases in total culturable fungal concentrations are also experienced in the summer months in Sydney.

The aim of this study was to provide information encompassing a broad range of aspects of indoor air pollutants relevant to public health for Sydney, with the goal of contributing to the development of more comprehensive urban indoor air quality guidelines for the wellbeing of building occupants.

The investigation comprised a field study of air pollutants in indoor office environments in Sydney, in the effort to elucidate:

- Baseline Indoor/Outdoor ratios of physicochemical pollutants for Sydney;
- Whether natural, mechanical and mixed-type ventilation systems affect the indoor air quality of Sydney's buildings

Further, the novel component of this study was the concurrent assessment of aeromycota along with other air pollutants. Thus, a separate range of hypotheses were developed for this data, in which the investigation aimed to determine:

- The diversity and abundance of indoor airborne fungal concentrations for urban Sydney including seasonal patterns;
- Whether building ventilation system type has a quantifiable effect on diversity and abundance of indoor airborne fungi;
- Baseline Indoor/Outdoor ratios of airborne fungi for Sydney

2. Methods

2.1 Study area

Sydney, Australia has a warm sub-tropical climate. Sydney ambient air quality is relatively good compared to many other countries, although concentrations of PM and NO_2 can exceed national standards on occasion [15]. The main contributing source of Sydney's air pollution is fossil fuel combustion, specifically motor vehicle exhaust; however, domestic wood smoke in winter, and bush fires in summer can cause severe pollution events for a few days a year [16]. Even though the ambient pollution levels in Sydney are low by world standards, the existing levels of air pollutants have been estimated to lead to 2% of total deaths per year [17]. The ambient indoor air quality across Sydney has not been well studied in the literature, and the contribution of outdoor air pollutants to indoor environments has not previously been described.

2.2 Buildings and Ventilation type requirements

Eleven buildings across central Sydney were selected for assessment. Buildings were selected having a range of uses in a commercial capacity, along with a close (<5 km) proximity to central Sydney, and their spatial distribution throughout the city centre. These parameters were important in the effort to represent the variability of city occupational workplace environments, while minimising variability in outdoor pollutants across sites due to the influence of suburban development, which could be expected to have highly variant air pollutant profiles, depending on local usage. The locations of the buildings are presented in Figure 1.

Of the eleven buildings, five utilised centralised mechanical ventilation systems (MVS) integrated into HVAC systems. Three buildings relied on natural ventilation (NV) through openings in the building envelope, and three utilised mixed model ventilation systems, combining natural and mechanical ventilation methods (CVS). The CVS method in all sampled buildings relied on mechanical supply and natural exhaust.

The experimental units in this study were single floors within each building that best represented the broader function of the buildings, rather than the whole buildings per se (i.e. we did not sample basements, plant rooms, non-utilised spaces etc.). The parts of the buildings sampled are detailed in Table 1.

Ventilation rates were not investigated for the eleven monitored buildings and were not known by the building managers at the five mechanically ventilated buildings, however, the focus of this investigation was to explore possible relationships between ventilation *types* and indoor air pollution levels and composition, as opposed to the influence of ventilation rates. In any case, ventilation rates for naturally ventilated buildings can be highly variable and difficult to determine with reasonable accuracy. All ventilation systems were assessed as within the typical range for their type, thus any differences in air quality between building types resulting from ventilation rates per se may reasonably be assumed to be endogenous for that style of building ventilation system.

Other than ventilation system type, other variables were selected to be incorporated into the analysis, *a priori*, which were thought to have a significant impact on the indoor environment. These variables were: building materials, flooring type, building age and population density. Data for these variables are also presented in Table 1.

2.3 Physicochemical air quality samples

All monitoring locations were in work areas that were temporarily unoccupied at the time of sampling. The specific area within the floors of the buildings in which sampling took place were randomised between successive sampling events to account for any intra-sample variability, if present. Air samples were collected from the sites using several portable instruments; CO_2, CO, VOCs, NO, SO_2, were measured with a Yessair 8-channel IAQ Monitor (Critical Environment Technologies). Total suspended particulate matter (TSP), respirable suspended matter (PM_{10}: suspended particles <10 μm in diameter) and very fine particulate matter ($PM_{2.5}$) were recorded with a DustTrack II Aerosol Monitor 8532 laser densitometer. NO_2 was recorded with a GasAlert Extreme T2A-7X9 (BW Technologies, Canada). All sampling equipment was calibrated in the laboratory prior to each field sampling.

2.4 Fungal air samples

Airborne fungal propagule samples were collected using a Reuter Centrifugal air sampler (RCS; Biotest Diagnostics Corporation, Denville, New Jersey, USA), fitted with Sabouraud's dextrose agar (SDX; Biotest AG, Germany). On return to the laboratory, samples were incubated for 7 days at 23°C. The lower incubation temperature (lower than the optimal 30°C for fungal growth) was selected to favour the growth of fungi adapted to the temperature of average indoor environments. Microscopic observation of colonies was performed using an Olympus BX 50 light microscope. Colonies were identified to genus level, utilising the descriptions and keys of [18-21]. When colonies were unidentifiable, colonies were subcultured onto new Sabouraud's Dextrose Agar

and re-incubated until sporulation. Colonies that did not have conidial structures or spores were grouped together as 'sterile mycelia'.

A matching outdoor fungal data set [10] was used to calculate indoor/outdoor (I/O) ratios. Only total airborne fungal concentrations were used here to calculate I/O ratios. Similarly, matched outdoor TSP, PM_{10}, $PM_{2.5}$, CO_2, CO, VOCs, NO, SO_2 datasets [20] were used to calculate I/O ratios for these variables.

2.5 Quality assurance

Walk throughs were undertaken for each building, in order to check for evidence of visible mould growth or water damage. Building occupants were asked whether they had any concerns about the general air quality of their workspace. Upon questioning, no building occupant had any complaints about the perceived air quality in their buildings. During the sampling duration, occupants were asked to close any obvious windows and openings to the outdoors, especially for that of the NV and CVS buildings so that any variability in outdoor wind velocity across sites would not affect the air quality of the sampled room at that time. All sampling equipment were calibrated prior to sampling. Reference data from three proximal air quality monitoring sites operated by the Office of Environment and Heritage NSW (OEH) NSW were obtained for comparison on the days on which samples were collected, for PM_{10}, $PM_{2.5}$, CO, NO_2 and SO_2. The reference sites included: Randwick (1 km from the closest sample site); Rozelle (3.5 km from the closest sample site) and Earlwood (10 km from the closest sample site). The OEH air quality monitoring sites utilise a tapered element oscillating microbalance (TEOM) for particulate matter quantification, as per the Australian Standard (AS 3580.9.8e2001), approved by the NSW EPA (2007). The average TEOM data sourced from these monitoring sites were used to monitor the accuracy of the particulate matter data obtained from the DustTrak. This was done by calculating the difference between the mean recorded data and the mean derived from the three OEH sites, and applying it as a correction factor for each sampling event.

2.6 Data analysis

Univariate data analysis was conducted using SPSS version 21.0 (SPSS Inc., USA) and multivariate analysis using PRIMER v6.1.6 (Primer- E Ltd, 2006).

Differences in air pollutant concentrations across building types were compared using repeated measures general linear model ANOVAs, with the between subject factors: building type, and the within subjects factor: month.

The combined air pollutant composition differences across months were compared using analyses of similarities (ANOSIM) using a 4th root transformation and the construction of a Euclidean distance similarity matrix. When fungal CFU/m^3 were compared across treatments, a Bray Curtis similarity matrix was constructed, since it is more robust for datasets with scant data [22]. Similarity percentages analysis (SIMPER) was used, to identify the air pollutants that were responsible for differences across groups (building type and months), i.e. the pollutants that were most different between the months and building ventilation system types. Statistical significance was tested at alpha = 0.05.

3. Results

Trends for TSP concentrations in buildings with the various ventilation system types and across months are displayed in Figure 2. The TSP concentrations at the sample sites were generally in the range of 14–42 $\mu g/m^3$ throughout all months of the year. Although no significant differences were found in TSP concentrations across treatments (GLM RM ANOVA, $P>0.05$) notable trends were observed, with mixed-ventilated buildings generally recording higher particulate matter concentrations than the other ventilation system types. This same trend was observed in the other fractions of particulate matter (Figure 3 & 4). No seasonal variation was observed in particulate concentrations. However, when analysing I/O ratios for TSP across building types, HVAC buildings rarely exceeded I/O values of 1, while buildings with NV and CVS consistently recorded I/O ratios over 1.

Concentrations of CO_2 are presented in Figure 5, with mean concentrations ranging from 395 ppm to 650 ppm. Some significant differences were present, with MVS buildings consistently recording significantly higher concentrations of CO_2 than those recorded for buildings with NV or CVS (RM GLM ANOVA, $P<0.05$ for both differences mentioned).

Values for NO_2 are presented in Figure 6, with mean concentrations ranging from 0.2 parts per hundred million (pphm) to 2.5 pphm. Although no significant differences were found in NO_2 concentrations across treatments (RM GLM ANOVA, $P>0.05$ for all comparisons), a noticeable increase in concentrations occurred for all building types during September, October and November; with NV buildings and CVS buildings experiencing the highest concentrations.

There was no significant difference in mean temperature across building type (RM GLM ANOVA $P>0.05$), however the temperatures in buildings with NV were more variable than the other building types. Temperature levels detected throughout the year ranged from 21.02^oC – 24.92^oC for buildings with MVS, 19.20^oC – 27.60^oC for buildings with NV, and 21.02^oC – 27.39^oC for buildings with CVS. There was no significant difference in mean RH across building type (RM GLM ANOVA $P>0.05$), however mean RH was significantly higher in all ventilation system types during summer months. The humidity levels detected ranged from 33.00 – 71.3 % for buildings with MVS, 33.8 – 60 % for buildings with NV, and 30.3 – 62.0 % for buildings with CVS. The values obtained lie generally within the optimal comfort range for building occupants of 40–60 % [23], with only occasional variation outside recommended levels.

Data for NO, TVOC, CO and SO_2 were consistently very low, below detection limits on many occasions and well below Air-NEPM standards. Consequently, these variables were not analysed individually, as these variables were too low to be a concern for the health of the building occupants. However, they were incorporated into the multivariate analyses, since there is evidence that multiple air pollutants may have additive effects.

Low concentrations of mould spores were encountered in samples across all sites and all months (Figure moulds, Table 2). Buildings with NV had higher mould spore concentrations relative to those that relied on air conditioning systems for ventilation. Buildings with high mould concentrations also supported higher diversity of fungal species. Buildings with HVAC had significantly lower mean numbers of fungal genera (GLM ANOVA $P < 0.05$) compared to the other ventilation system types. The other ventilation system types both supported statistically similar fungal densities (GLM ANOVA; $P > 0.05$).

Cladosporium was the most frequent genus encountered in CVS buildings, being found in 75.7% of samples, with a mean of 118 CFU/m^3. No other genus had a mean greater than 50 CFU/m^3 in these buildings; however *Penicillium* and *Alternaria* were also relatively frequently encountered, occurring in 45.9 and 43.2% of samples respectively.

Sterile mycelia were the most frequently identified in NV building samples, found in 59.5% of samples and displayed a mean of 54 CFU/m^3. Other genera that showed a mean of greater than 50 CFU/m^3, were *Cladosporium* (139 CFU/m^3), *Alternaria* (55 CFU/m^3) and *Penicillium* (81 CFU/m^3), occurring in 56.8, 54.1 and 45.9% of samples respectively.

The most frequently identified fungi identified in MVS buildings were yeasts, which were detected in 54 % of samples with a mean of 40 CFU/m^3, followed by *Cladosporium* at 51% with a mean of 68 CFU/m^3. Yeast isolates were tested with a capsule stain to determine whether there was a possibility of *Cryptococcus* spp; however, none were found. When comparing the combined air pollutant data composition across building type, significant differences were observed (ANOSIM; Global R = 0.112, P = 0.01); with differences identified between MVS buildings and both buildings with CVS buildings (r=0.114; p=0.002) and NV buildings (r=0.160; p=0.001). There were also a minor difference between buildings with CVS and buildings with NV (r=0.042; p=0.045).

SIMPER analysis determines the data variables that contribute most strongly to group differences in a multivariate dataset, i.e. which variables were the most different between the building types. In all cases, SIMPER analysis identified that buildings with HVAC had lower concentrations of almost all pollutants than the other building types, with lower concentrations of total fungal CFU/m^3 as the primary contributor to the overall building differences, followed by TSP. The only air pollutant not to follow this trend, was ambient CO_2 which was persistently higher in concentrations in MVS buildings, and the main contributor to the overall differences between CVS and MVS buildings, along with the overall differences between NV buildings and MVS buildings.

Significant differences were observed amongst the structure of airborne fungal communities across building types (Global R = 0.135, P = 0.010), with MVS buildings significantly different to CVS (r=0.122; p=0.001) and NV buildings (r=0.255; p=0.001). In all cases, SIMPER analysis identified increased concentrations of *Cladosporium* as the primary taxon differentiating the HVAC buildings from the other building types (10.3% - 10.7 % of the between-building differences), followed by yeasts and *Penicillium* (>8.94 % and >8.91% of between building differences respectively). No other taxa contributed more than 8 % of the overall observed differences between building types.

I/O ratios for TSP generally ranged between 0.53 and 2.48 across all building types, with indoor concentrations rarely exceeding those encountered outdoors for MVS buildings, however NV and CVS buildings I/O ratios were near parity or exceeding 1 on numerous occasions; this same trend also occurred for the other particulate fraction types. I/O ratios for CO_2 concentrations ranged between 0.98 and 1.57 across all samples; with all building types generally having higher concentrations indoors than outdoors; however MVS buildings continually experienced higher ratios with 1.21 being the lowest I/O ratio recorded. I/O ratios for NO_2 concentrations ranged between 0.20 and 3.33 for all building types; with all building types rarely experiencing higher concentrations indoors than outdoors. I/O ratios for bioaerosols generally ranged between 0.18 and 1

across all building types, with indoor concentrations rarely exceeding those encountered outdoors. Data for I/O ratios for all data variables measured is presented as supplementary data.

4. Discussion

The current study provides an assessment on the density and prevalence of air pollutants in the indoor air in a sub-tropical environment for Sydney. In doing so, it has been demonstrated that differences in air quality occur across different ventilation system types. MVS buildings recorded the lowest PM concentrations and fungal bioaerosols. Few studies have sought to make a quantitative determination of indoor particulate concentrations with different ventilation systems, including natural ventilation [7]. MVS buildings can prevent the intrusion of a large fraction of particulate matter [7], as was evident in this study, with I/O ratios for TSP, PM_{10} and $PM_{2.5}$ all below 1 for MVS buildings, and significantly lower than the I/O ratios for the other building types.

Air NEPM recommends a limit of 50 $\mu g/m^3$ for daily PM_{10} exposure and 25 $\mu g.m^3$ for daily $PM_{2.5}$ exposure. The PM_{10} levels recorded in this study never exceed the limit for PM_{10}, however, mean $PM_{2.5}$ concentrations were exceeded during October for CVS buildings. Interestingly, the I/O ratio for $PM_{2.5}$ for CVS buildings during October was 1.25, indicating that there were potentially indoor sourced pollutants in those buildings during that time.

A noticeable increase in NO_2 concentrations occurred for all building types during September, October and November; with NV buildings and CVS buildings experiencing the highest concentrations. The WHO Guidelines propose a limit of 200 $\mu g/m^3$ or 10.6 pphm limit, while Air-NEPM proposes a 12 pphm maximum limit. In this study no buildings exceeded those limits on the days in which sampling took place. Similarly, levels of personal NO_2 exposure in another Australian city, Canberra, have been shown to be relatively low, with a median concentration of 0.83 pphm [24]. Low indoor NO_2 concentrations (median 0.6 pphm) have also been reported in a study from Latrobe, Australia [25], additionally finding I/O ratios near 1 for all building types indicating that street level concentrations of NO_2 seemed to have sizeable influence on indoor concentrations. In contrast, other research in six European cities found that NO_2 is often found at higher concentrations indoors than outdoors [26], possibly a consequence of indoor sources like smoking which is banned in occupational environments in Australia. However, in this study, indoor concentrations were only higher than outdoor concentrations sporadically, with no discernible trend when these events did occur. The range in predicted relative indoor to outdoor concentrations of NO_2 is 0.3 to 1.6 [27], which is much smaller than the range for other air pollutants because of losses of NO_2 via sorption on surfaces. If outdoor NO_2 concentrations are relatively close to those found indoors, ventilation rates will likely cause negligible changes in indoor NO_2 concentrations [28]. In Sydney and many other major cities, ambient atmospheric NO_2 is derived from vehicle use and combustion processes, and thus the increased concentrations in Australian cities during Spring and Summer appear to be connected with bush fires, which are frequent in these months [15]. A study by Challoner and Gill [29] demonstrated that lower indoor NO_2 concentrations were present in naturally ventilated buildings compared to the MVS buildings. The authors attributed these observations to the deposition of NO_2 on the internal surfaces as well as possible heterogeneous reactions in these older buildings, although as found in this study, most buildings showed strong temporal relationships between outdoor and indoor NO_2 concentrations.

Although MVS buildings had fewer physical contaminants, they presented mean CO_2 concentrations consistently higher than both of the other ventilation types. This is potentially a result of the HVAC buildings

having a larger population density of occupants than the other building types (Table 1), and therefore containing greater respiratory CO_2 emissions. Whilst CO_2 concentrations were higher in these buildings, no mean CO_2 concentrations exceeded the time weighted average of 5000 ppm set by Work Safe Australia [30], nor the 1000 ppm, which is the maximum indoor standard specified by American Society of Heating, Refrigeration and Air Conditioning Engineers for air-conditioned buildings [31].

The I/O ratios explain why, on occasion CVS buildings recorded higher concentration of some pollutants than NV buildings and MVS buildings. As I/O ratios rarely exceeded 1 for any treatment, we deduce that there was no obvious evidence of indoor sources contributing to the air quality of the buildings.

As with this study, an investigation in East Brisbane [34], documented a comparison of the ratios of indoor to outdoor particle concentrations, revealing that while the ratio varies across a broad range from 0.2 to 2.5, average values of the ratios were very close to 1, regardless of ventilation conditions and of particle size range. Under ideal conditions, mechanical intake ventilation systems equipped with a good filter can remove most of the coarse particles from the air coming indoors (greater than 70 % of $PM_{2.5}$) [35].

Total fungal concentrations indoors were consistently below those outdoors, and no sample clearly indicated fungal contamination in any building. The WHO proposes a guideline value of 500 CFU/m^3 for indoor airborne fungal concentrations [36], and any values higher than this require further investigation due to the potential of indoor sources. International organizations such as International Society of Indoor Air Quality and Climate (ISIAQ), American Conference of Governmental Industrial Hygienists (ACGIH) and American Industrial Hygiene Association (AIHA) recommend that, for buildings without visible fungal damage, the composition of airborne fungal species should resemble those occurring outdoors [37]. These guidelines also indicate that fungal concentrations ranging between 100 and 1000 CFU/m^3 represent general indoor and outdoor concentrations [37, 38]. Further, the persistent presence of potentially pathogenic or toxigenic fungi such as *Stachybotrys* or *Fusarium* spp. is unacceptable at any propagule concentration and the measurement of any single species must be no more than 50 CFU/m^3. In the present study, neither of these toxigenic genera were identified in the air samples, however, MVS buildings did exceed the total fungal concentration guideline during May, the mean CVS building concentration exceeded this value for 4 months of the year, while the mean airborne fungi from NV buildings exceeded this value for 6 months of the year. Although these values may appear high, the fungal I/O ratios need to be taken into consideration for tropical and subtropical areas, as outdoor concentrations can be extremely high due to the conducive climate in these regions. Salonen *et al.* [39] frequently found high (> 1000 CFU/m^3) total culturable fungi outdoor levels in naturally ventilated buildings in Brisbane throughout the year, even during subtropical winter time, and these findings were found to correspond to high fungal levels in indoor air. They suggest that in subtropical areas, the concentration of culturable fungi in indoor air should be always taken concurrently with outdoor air concentrations to eliminate the effects of high ambient levels. In the current study I/O ratios rarely exceeded 1, with all building types frequently recording lower concentrations indoors than outdoors throughout the entire year, although, outdoor concentrations did on occasion exceed 1000 CFU/m^3. This indicates that for the most part, even for the naturally ventilated buildings studied, these particles are not penetrating into the buildings. This finding is similar to a previous study of over 1700 buildings throughout the US, which found that 85 % of the buildings had I/O ratios of 1 or lower for total fungi [40].

It has been reported that in HVAC buildings, the effect of seasonal variation on the fungi found in indoor air is diminished [41]. This phenomenon was evident in the current study, with NV and CVS buildings recording higher concentrations during summer months, whilst HVAC mean concentrations were relatively consistent throughout the entire year. This seasonal periodicity was expected, as the factors that influence the proliferation of moulds (humidity, warm temperature and rainfall) also fluctuate throughout the year. The major determinants of total airborne fungi in ambient outdoor air for Sydney, in rank order, have been identified as proximal greenspace, wind speed, and rainfall [10]. As these factors are not as influential in indoor environments as they are to outdoor environments, their effect may only be observed on the diversity and volume of fungi for buildings with natural ventilation, whereas in buildings with a mechanical air intake, the concentrations are more stable due to the filtration of outdoor fungal material [42]. This pattern was observed in this investigation, with I/O ratios for buildings with HVAC consistently lower than the ratios recorded for the other building types. Whilst air filtration systems may represent a good solution for the improvement of the particulate components of indoor air quality (IAQ), there is potential for organic matter to accumulate on the filter, facilitating microbial growth, which consequently leads to reduced filter efficiency and filter degradation [43], and the potential for the re-emission of biological contaminants.

Irga and Torpy [10] found few pathogenic fungi in outdoor air samples for this study area, and the densities of the allergenic groups of most concern, including *Alternaria*, were within an acceptable range for human health. A small number of potentially opportunistic organisms of concern for human health were encountered in the current work: for example, several *Aspergillus* spp. were documented, and only in the CVS and NV buildings. No dimorphic or systemic pathogens were detected, nor were any dermatophytes.

Significant differences were observed when comparing the airborne fungal community structures amongst building types, with MVS buildings significantly different to CVS and NV buildings. Lower concentrations of *Cladosporium*, yeasts and *Penicillium* in the MVS buildings were the major taxa in these community driven differences. *Aspergillu*s and *Penicillium* are usually more considered as indoor genera [44], whereas *Cladosporium* and *Alternaria* contamination are more linked to outdoor sources [45]. *Aspergillus*, *Penicillium*, yeasts and bacteria were detected more frequently indoors compared with outdoors, however for yeasts, indoor relative humidity was the only independent predictor of high airborne concentrations [46].

5. Conclusion

The concentrations of air pollutants in a sample of indoor office environments in Sydney were tested, and found to be below guidelines levels. Generalizing, it is likely that the indoor air quality of a typical Sydney building is relatively good. The ventilation type of the buildings did affect indoor air quality; however not to the extent that occupant health was at risk in any case. Our findings thus indicate that if a building is to be constructed in a region of a city of similar structure, climate and ambient pollutant concentrations to Sydney, the use of CVS and NV could provide an indoor environmental quality of a sufficient standard, thus saving the major infrastructure and running costs associated with MVS. However, a localized study should always be performed prior to implementation to ensure that unsafe conditions will not arise.

Low concentrations of airborne fungi were encountered in samples, across all sites and across months, with naturally ventilated buildings tending to have higher concentrations. Buildings with high airborne fungal

concentrations also supported higher diversity of fungal species. *Cladosporium* was the most frequent genus encountered, followed by *Penicillium* and *Alternaria*. No organisms of concern to public health were identified. Building ventilation type was assessed to determine whether it had a quantifiable effect on the diversity and abundance of indoor airborne fungi. Significant differences were observed when comparing airborne fungal communities across building types, with MVS buildings significantly different to the other ventilation types. Differences in concentrations of outdoor sourced *Cladosporium* cause the majority of these differences, being higher in buildings with a natural ventilation component, followed by yeasts and *Penicillium*.

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Table 1. Attributes of the sampled buildings. MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed model ventilation system.

Site	Coordinates		Approximate age (years)	Surface area of sampled indoor space (m^2)	Floor sampled / number of floors	Material	Floor type	Estimated population density (persons / 10 m^2)
MVS1	-33°52’23”	151°12’18”	35	1220	3/24	Concrete	Tiled	0.98
MVS2	-33°52’26”	151°12’29”	40	467	7/16	Concrete	Carpet	0.75
MVS3	-33°52’48”	151°12’09”	25	10971	3/5	Brick	Carpet	0.88
MVS4	-33°53’10”	151°12’50”	2	508	2/3	Glass / Steel	Tiled	0.70
MVS5	-33°54’44”	151°10’57”	10	392	2/2	Concrete	Carpet	0.75
NV1	-33°52’26”	151°13’43”	85	152	2/2	Timber	Timber	0.05
NV2	-33°53’18”	151°12’13”	3	595	1/1	Brick	Timber	0.60
NV3	-33°54’04”	151°13’24”	110	402	2/3	Brick	Carpet	0.10
CVS1	-33°53’16”	151°11’46”	50	636	3/3	Brick	Carpet	0.35
CVS2	-33°52’56”	151°11’06”	130	473	1/2	Brick	Timber	0.50
CVS3	-33°54’39”	151°12’27”	25	498	2/2	Brick	Linoleum	0.65

Table 2. Total frequency (% incidence in samples), mean and max (CFU/m^3), for airborne fungal genera identified in indoor air samples across ventilation types. MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed model ventilation system.

CVS				NV				MVS			
Genus	Freq (%)	Mean CFU/m^3	Max CFU/m^3	Genus	Freq (%)	Mean CFU/m^3	Max CFU/m^3	Genus	Freq (%)	Mean CFU/m^3	Max CFU/m^3
Cladosporium	75.7	118.06	800	Sterile Mycelia	59.5	54.17	200	Yeasts	54.4	40.63	200
Penicillium	45.9	47.92	450	*Cladosporium*	56.8	139.58	1350	*Cladosporium*	51.1	67.92	500
Alternaria	43.2	47.22	250	*Alternaria*	54.1	55.56	300	*Alternaria*	34.6	39.38	550
Sterile Mycelia	43.2	45.83	225	*Penicillium*	45.9	80.56	600	*Epicoccum*	33.0	21.25	150
Yeasts	37.8	36.11	250	Yeasts	27.0	20.83	200	*Aspergillus*	32.4	13.30	300
Epicoccum	29.7	22.92	150	*Cladophialophora*	24.3	28.47	250	Sterile Mycelia	31.3	20.00	200
Aspergillus	24.3	24.70	450	*Aspergillus*	24.3	27.10	600	*Penicillium*	29.7	46.25	1200
Acremonium	21.6	9.72	75	*Aureobasidium*	21.6	14.58	250	*Acremonium*	18.1	15.00	200
Cladophialophora	21.6	14.58	125	*Phoma*	21.6	13.19	100	*Scopulariopsis*	18.1	8.33	150
Fusarium	18.9	10.42	150	*Epicoccum*	18.9	16.67	150	*Phoma*	16.5	9.17	100
Curvularia	13.5	9.72	150	*Curvularia*	13.5	6.94	75	*Aureobasidium*	11.5	6.46	100
Phoma	13.5	6.94	100	*Fusarium*	13.5	11.81	150	*Verticillium*	9.9	5.00	150
Aureobasidium	10.8	4.86	50	*Malbranchea*	13.5	6.25	50	*Curvularia*	8.2	5.00	150
Malbranchea	10.8	6.94	100	*Rhizopus*	13.5	9.03	150	*Cladophialophora*	6.6	2.50	50
Pithomyces	10.8	4.86	75	*Acremonium*	10.8	6.25	100	*Beauvaria*	4.9	3.33	100
Scopulariopsis	10.8	4.86	50	*Botrytis*	10.8	6.94	100	*Fusarium*	4.9	2.08	50
Rhizopus	8.1	5.56	100	*Beauveria*	8.1	5.56	100	*Nigrospora*	4.9	2.08	50
Nigrospora	5.4	1.39	25	*Mucor*	8.1	4.17	50	*Trichothecium*	4.9	1.46	50
Paecilomyces	5.4	1.39	25	*Nigrospora*	5.4	1.39	25	*Cunninghamella*	3.3	1.67	25
Stemphylium	5.4	4.17	100	*Stachybotrytis*	5.4	4.86	150	*Paecilomyces*	3.3	0.83	25
Verticillium	5.4	6.94	200	*Stemphylium*	5.4	2.78	50	*Trichoderma*	3.3	2.50	100
Basidiobolus	2.7	1.39	50	*Trichoderma*	5.4	3.47	100	*Botrytis*	1.6	0.42	25
Beauveria	2.7	1.39	50	*Verticillium*	5.4	2.78	50	*Chaetomium*	1.6	0.42	25

Cunninghamella	2.7	0.69	25		*Ulocladium*	5.4	2.78	50		*Chrysosporium*	1.6	0.83	50
Fonsecea	2.7	1.39	50		*Bipolaris*	2.7	1.39	50		*Fonsecea*	1.6	1.67	100
Lecythophora	2.7	2.78	100		*Chrysosporium*	2.7	1.39	50		*Geotrichum*	1.6	0.42	25
Chaetomium	2.7	1.39	50		*Cunninghamella*	2.7	0.69	25		*Madurella*	1.6	0.83	50
Scytalydium	2.7	1.39	50		*Dreschlera*	2.7	0.69	25		*Ulocladium*	1.6	0.83	50
Trichoderma	2.7	1.39	50		*Fonsecea*	2.7	1.39	50					
Veronea	2.7	1.39	50		*Geotrichum*	2.7	1.39	50					
					Gliocladium	2.7	1.39	50					
					Chaetomium	2.7	5.56	200					
					Pithomyces	2.7	1.39	50					
					Scopulariopsis	2.7	0.69	25					
					Veronea	2.7	11.11	400					

Figure Legends

Figure 1. Map showing the locations of the eleven sampling sites in Central Sydney.

Figure 2. Average concentrations of total suspended particles (TSP) in the atmosphere of buildings with different ventilation types, over a 12-month period (Means ± SEM). MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed model ventilation system.

Figure 3. Average concentrations of particulate matter <10 µm (PM_{10}) in the atmosphere of buildings with different ventilation types, for the over a 12-month period (Means ± SEM). MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed model ventilation system.

Figure 4. Average concentrations of particulate matter <2.5 µm ($PM_{2.5}$) in the atmosphere of buildings with different ventilation types, for the over a 12-month period (Means ± SEM). MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed model ventilation system.

Figure 5. Average concentrations of atmospheric CO_2 for the three building ventilation types, over a 12-month period (Means ± SEM).

Figure 6. Average concentrations of atmospheric NO_2 for the three building ventilation types, over a 12-month period (Means ± SEM).

Figure 7. Average total number of fungal CFU/m^3 encountered across the three building ventilation types over a 12-month period (Means ± SEM).