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Indoor air quality and early detection of mould growth in residential buildings: a case study

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Covering letter to the Editor

One on three homes, worldwide, suffer from excessive dampness and mould proliferation, which is exacerbated by inadequate architectural strategies, poor construction practices and bad maintenance, resulting from a lack of awareness and knowledge in the construction sector about the topic. Indoor mould is correlated to severe adverse health symptoms, such as severe allergic asthma, hypersensitivity pneumonitis and allergic alveolitis, allergic rhinitis and sinusitis. The issue is further magnified by the difficulty of detecting mould before it is fully germinated. Indeed, the visible manifestation happens only at the final proliferation stage, which usually starts within the building envelope. An early detection of mould growth is key to prevent serious significant and serious health consequences, as well as extensive remediation interventions.

Most of the literature focus on analysing consequences, providing robust mould growth models, and identifying suitable strategies to prevent growth during the design stage. However, there is an urgent need for more evidence about the correlations between mould growth and the general indoor air quality to define possible indicators that can be used as proxy for detection of mould growth. This paper delves into this issue by presenting a case study where indoor air quality monitoring and mould inspections were prompted by the unexplained (and undiagnosed) deterioration of one occupant's health. This paper represents an exploratory study about the possibility to link indoor air pollutants and mould growth in detection strategies, and it paves the way for further analysis to be undertaken as part of a broader research project.

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Abstract Mould growth affects 1 in 3 homes, and it is the biggest cause for complaints and litigations filed to the relevant authorities in Australia, while significantly affecting the physical and psychological health of the building occupants. Indoor mould is caused by excessive dampness, resulting from poor architectural specification, construction and maintenance practices, as well as inappropriate occupants' behaviour. The consequences range from early biodeterioration of building materials, requiring anticipated renovation works, to deterioration of the indoor environment, posing a serious threat to the building occupants. This study investigates indoor air quality and mould growth, providing a snapshot of the current indoor air quality of Australian residential buildings regarding air pollutants. It uses a case study representative of the typical Australian suburban home to investigate the effects of unnoticed mould growth. Results of the monitoring campaign indicate that buildings with a high concentration of fungal spores are also more likely to present poor indoor air quality levels, high concentrations of particulate matters (PM_{10} and $PM_{2.5}$) and CO_2. This research suggests the need for the development of early detection strategies that could minimize the health hazard to people, thereby preventing the need for a major renovation.

Keywords: mould growth; hygrothermal; indoor environment; health; sustainability; indoor air quality

1. Introduction

Considering that humans spend a substantial amount of time indoors, Indoor Air Quality (IAQ) has to potential to significantly impact people's health and wellbeing [1, 2]. The IAQ contributing factors can be divided into physical parameters, such as temperature and humidity, chemical parameters, such as concentration of pollutants and substances in the air, and biological parameters, which include the presence of organic compounds and mould [3, 4, 5]. Indoor mould growth prevalence is further amplified by inappropriate design strategies [7], poor construction and maintenance practices [8], and occupants' habits [4, 8, 9] that may lead to indoor accumulation of moisture or condensation within the envelope [10]. Despite its great influence, mould growth is seldom considered nor well specified in building codes [4], and the lack of standard makes it difficult to establish its exact prevalence and diffusions.

Excessive dampness and indoor mould are estimated to affect between 10% and 50% of the global building stock, a percentage that is likely to be even higher in less privileged communities making exposure to mould a significant risk factor to individuals and communities [6]. Indeed, the digesting process of fungi growing within the building envelope reduces the building materials and components service life [11], and the early biodeterioration requires anticipated and extensive renovation works, with the consequent economic loss [8, 9, 12, 13]. Further, long exposure to indoor mould can have adverse health impacts with different degrees of severity. Generally, asthma appears to be the most diffused symptom of exposure [14], with an estimate indicating mould as responsible for 21% of the confirmed asthma cases in US [15], followed by other forms of allergies, such as pneomunitis, alvelotis,

allergic rhinitis and sinusitis [12, 16, 17]. In general, indoor mould affects the psychological wellbeing of the occupants of affected buildings, which can experience a sense of fatigue and reduction of the capacity to concentrate [18], with cases escalating to cognitive impairment and reduced productivity at work [18, 19]. These issues are further amplified by the difficulty of detecting mould before it is fully germinated [20], highlighting the importance of early detection of indoor mould presence.

In Australia, one in three homes suffers from mould growth [20] with evidence indicating that design and construction practices, systematically, do not properly consider moisture and moisture-related issues [4, 21]. For example, the National Construction Code (NCC) introduced hygrothermal provisions for the envelope design for the first time in 2019 [22] and with a specific focus on residential new construction only. These new provisions, coupled with the increasingly stringent thermal and airtight requirements developed as energy efficiency measures to respond to the international call for action against climate change, contributed significantly to the rapid rise of indoor mould cases in newly built homes [4, 13]. On the other hand, older buildings are prone to mould growth due to poor thermal insulation and the presence of thermal bridges [8], making mould an issue that transcends the age of construction. These inherent issues of the Australian construction industry are further magnified by the repercussions of climate change and the impacts of the global pandemic. On one side, increased levels of humidity, warmer summers, more frequent extreme weather events, such as flooding, and prolonged rainy periods create favourable conditions for mould to grow. On the other side, building occupants spending more time at home are both increasing the indoor moisture generation [23] and their exposure time, posing a serious health threat. This is even more pronounced within vulnerable communities, rentals and social housing due to a combination of poor building and environmental performance and financial limitations and/control over remediation [4].

This study aims to explore the correlations between air pollutants, indoor air quality and biological growth in the Australian context. The ultimate goal is to develop a better understanding of possible indicators of mould presence that can be diffusely used for early detection, which, in turn, may prevent serious health implications and significant economic loss.

2. Methods

This scoping study undertakes an empirical investigation of a case study conducted on a residential building, which can be considered as the typical Australian dwelling. The investigation included a site inspection, air testing and surface swabs for mould detection, as well as a monitoring indoor air quality (IAQ) campaign two-month long (during winter). This analysis has been prompted by adverse health symptoms observed in one building occupant, which were not followed by clinical reasons.

2.1 Case study

The case study is a two-storey residential building located in Gowrie, a suburb of Canberra ACT, Australia. The dwelling is a typical reversed brick veneer with timber frame, and it can be considered a good representation of the

average Australian home. More than two third of Australians live in similar single family or semi-detached town houses [24], making this case study highly representative of a bigger cohort of buildings. This building was built before 1988 and, at the time of investigation, did not undertake any major renovation. The architecture of the building comprises a split level with high raked ceilings and a mezzanine level, four bedrooms and two bathrooms. The bedrooms, bathrooms, laundry and kitchen face South with no direct solar entrance (southern hemisphere), while the lounge and entry face the North, as represented in Figure 1. A closed fireplace is located between the kitchen and the lounge.
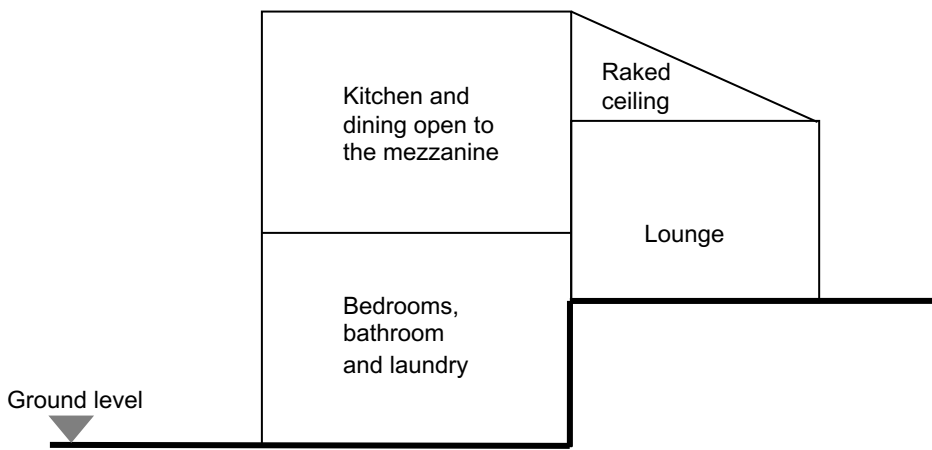

Figure 1: Diagram of the vertical distribution

Canberra (ACT, Australia), where the building is located, is characterized by an oceanic climate [25], where the warmest month has a mean maximum temperature of 30.6°C but can register temperatures around 0°C with frequent frost during July (Table 1), when the mean number of days with temperatures below zero is 16.

Table 1: Monthly mean temperature in Canberra [22]

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Mean max temp [°C]	30.6	28.1	25.0	21.0	16.6	13.4	12.7	14.1	18.0	21.5	24.9	27.5
Mean min temp [°C]	14.2	13.5	11.1	6.8	2.4	1.2	0.1	0.9	3.1	6.2	9.8	12.1

This area is also characterized by frequent precipitations. The annual average is approx. 700mm, with the highest intensity registered in October (66mm) and the lowest in June (38.1mm) [25]. In average, there are around 100 days of precipitations per year, with July being the wettest month (11 days of precipitation) and April the driest (6 days) [25].

2.2 Monitoring campaign

The experimental campaign involved inspections, mould detection and IAQ monitoring. The initial inspection took place on June 2020, and it aimed at detecting potential risk source and understanding occupancy habits to inform the monitoring campaign, which started in early July 2020. Table 2 shows the parameters monitored during the

experimental campaign. During July, several mould swabs have been taken around the house with the scope of identify potential fungal strains, using air sampling cassettes, based on inertial impaction (the cassette is provided with a tapered inlet that directs particulate laden air towards a slide with the collection media) and characterized by a detection limit of 38 FS/m^3, and surface swabs, with a detection limit of 4 FS/m^3.

Table 2: IAQ monitoring equipment

Parameter	Sensor type	Accuracy	Resolution	Range
PM_{10}; $PM_{2.5}$	Light scattering (350nm)	±10% (<30µg/m^3 ±3µg/m^3)	1µg/m^3	1 / 100030µg/m^3
CO_2	Non-dispersive infrared	±3% ±50ppm	1ppm	400 / 2000ppm
TVOC	MOS	±15%	1ppb	N/A
Temperature	Digital	±1°C	1°C	-200 / 100°C
Relative humidity	Digital	±5%	1%	0 / 99%

3. Results and discussion

3.1 Site inspections

During the initial inspection of the building, several risk factors for mould growth and poor IAQ were noticed. The lower level was characterized by poor lighting, with very low daylight levels. This space was designed to be lit by the windows in the bedrooms, which were, however, kept always closed and equipped with sunblock curtains, as not occupied. Further, this contributed to reducing at minimum natural cross ventilation throughout the lower level, where also wet and humid rooms, such as bathrooms and laundry, are located and, consequently, preventing moisture laden air to be correctly exhausted by those rooms. This situation was aggravated by a leaky wall cavity from the shower, which were damaging the surrounding walls. All these details indicated that indoor mould was likely to be found in this area of the dwelling.

The mould sampling results reveal that indoor mould was highly diffused in the apartment, as indicated in Table 3.

Table 3: Results of the mould sampling (expressed in FS/m^3)

Sample		Total fungal structures	Mould genera	
Air sample	Kitchen	3994	*Aspergillus / Penicillium*	2765
			Basidiospores	499
			Cladosporium	77
			Smut / Myxomyces / Periconia	269
	Hallway	5760	*Alternaria*	38
			Aspergillus / Penicillium	2918
			Basidiospores	998
			Cladosporium	154
			Curvularia	38
			Spegazzinia	154
	Bedroom (occupied)	9638	*Aspergillus / Penicillium*	7680
			Basidiospores	806
			Bipolaris / Drechslera	38
			Cladosporium	154
			Oidium / Peronospora	38
			Smut / Myxomyces / Periconia	192
Surface swab	Kitchen bench	83	*Ascospores*	8
			Aspergillus / Penicillium	75
	Hallway cupboard	17	*Aspergillus / Penicillium*	17

| | Bedroom (occupied) | 46 | *Aspergillus / Penicillium* | 38 |
| | | | *Basidiospores* | 8 |

Results identify aspergillus spp as predominant mould genera, which confirms the literature [4]. This fungal strain is among the most common, yet one of the most critical for human health [12], being responsible for various insidious infections and correlated to the sick building syndrome [26]. Cladosporium is more commonly found on exterior facades [4] and its detection indoor suggests a potential exchange of spores within the outdoor. Nonetheless, at least 24 different fungal strains were detected, of which 50% are usually regarded as a source of raspatory infections, 21% able to produce mycotoxins, which constitutes a second health hazard, and 25% usually considered a proxy for condensation issues. As expected, the bedrooms and the hallway presented a higher concentration of spores, due to the high humidity accumulated indoor by poor ventilation practices and water leakages in the envelopes. Unexpectedly, the kitchen also shows elevated spore concentrations, albeit lower than the other rooms. These results indicate that the effects and implications of indoor mould may affect a much larger area than the affected surface, mainly due to the volatile nature of spores and mycotoxins combined with a higher cleaning frequency of surfaces with antibacterial products. In this case, mould was expected in the unoccupied rooms, but effectively found across the whole dwelling, determining a high risk for the occupants.

3.2 IAQ monitoring and sampling

The indoor environmental parameters have been monitored between June 28th June and September 9th of 2020. Acceptability thresholds for indoor pollutant concentrations have been considered as shown in Table 4.

Table 4: Measured PM_{10}, $PM_{2.5}$, CO_2 and TVOC values and Indoor Air Quality thresholds

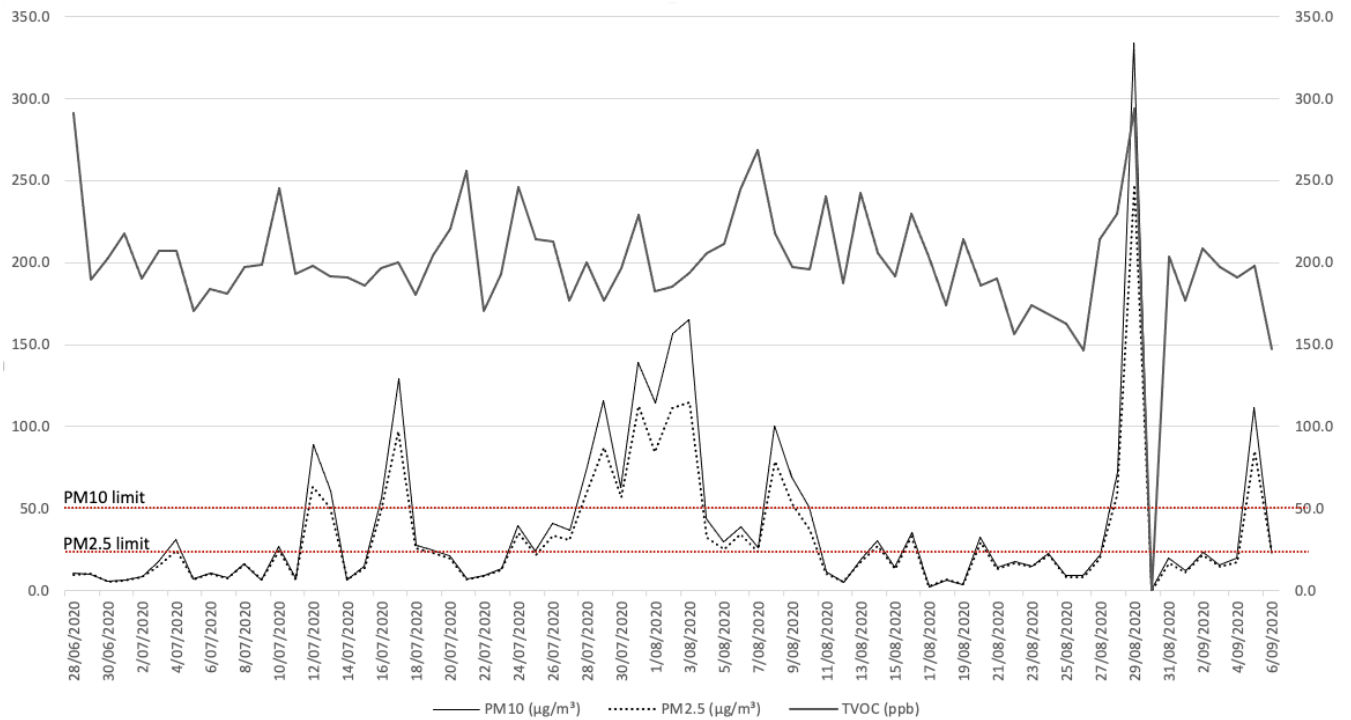| Parameter monitored	Acceptable threshold	Note
PM_{10}	50 μg/m^3	Averaged on 1 hour. Exceptional event rule: an exceptional event is a fire or dust occurrence that adversely affects air quality at a particular location; causes an exceedance of 1one-day average standards in excess of normal historical fluctuations and background levels, and is directly related to bushfire, jurisdiction-authorised hazard- reduction burning or continental-scale windblown dust [27].
$PM_{2.5}$	25 μg/m^3	
CO_2	850ppm	Averaged on 8 hours. NCC IAQ Verification Method This level is based on an increment of 450ppm above the background CO2 concentration, representing an adequately ventilated building [27].
TVOC	500 μg/m^3	Averaged on 1 hour [27].

Figure 2: Monitored values of PM$_{10}$, PM$_{2.5}$ and TVOC

Figure 2 shows the results obtained from monitoring of indoor PM$_{10}$, PM$_{2.5}$ and TVOC values. Based on the defined acceptability limits (Table 4), the IAQ analysis shows that pollutants' concentrations have been consistently higher than the expected thresholds, especially during the periods of 13/07, 17/07/, 29/07, 01/08-04/08, 09/08, and 29/08. A similar general pattern is exhibited for both PM$_{2.5}$ and PM$_{10}$ values. The difference between the defined threshold and measured PM values were approximately 225μg/m^3 and 280μg/m^3 for PM$_{2.5}$ and PM$_{10}$ values, respectively. The peak values observed in the measurements overlap with the rainy days recorded during those periods [BOM, weather data from the closest weather station Tuggeranong AWS]. Days with high rainfall over 10mm were 13th, 26-27th July and 8-9th August. However, no rainfall was registered during 29/08, hence the peak indoor measurements are due only to indoor pollutants.

The TVOC level was always lower than the defined threshold (500μg/m^3) [27] for the whole duration of the monitoring campaign, ranging between 150-250. The peak was registered on 29/08, showing a similar trend observed for PM$_{2.5}$ and PM$_{10}$.
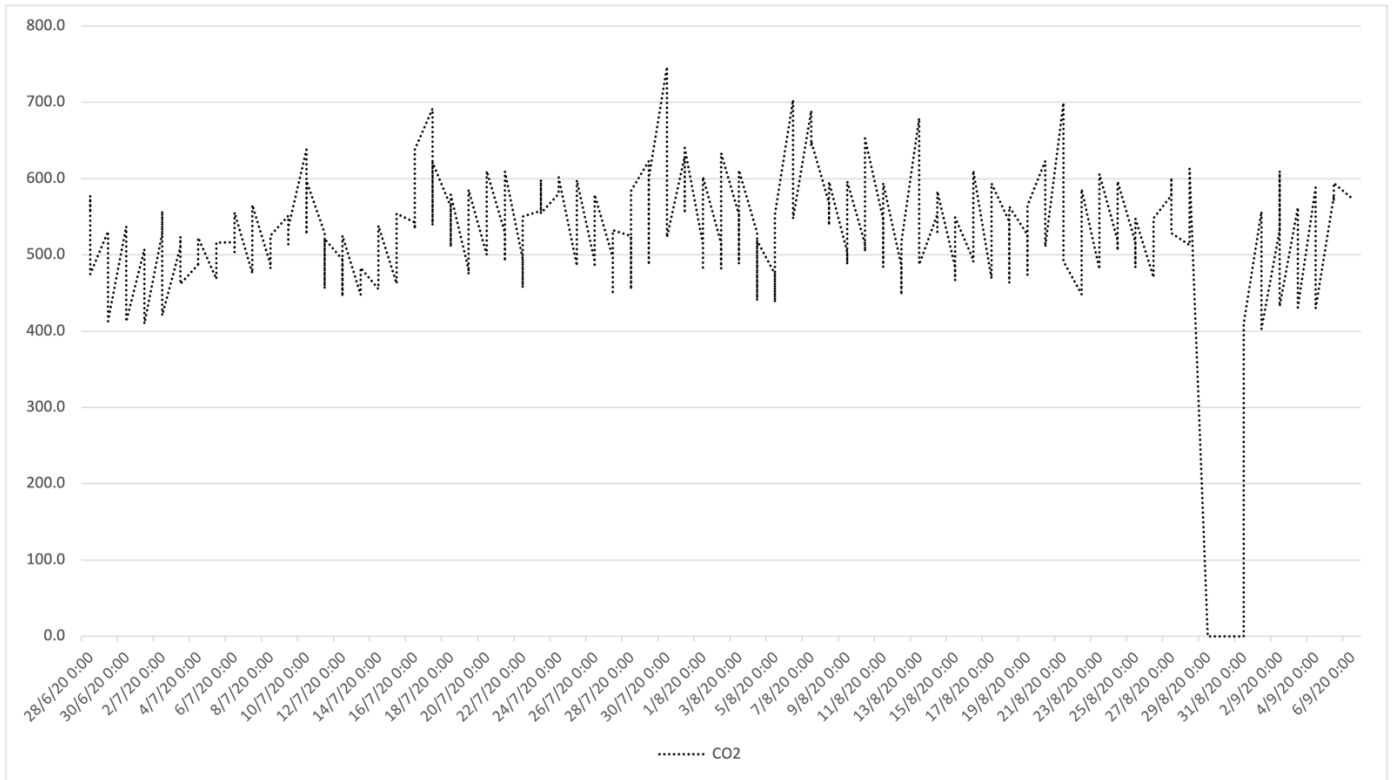
Figure 3: Monitored values of CO₂ (from 29/08 to 31/08 sensors not working)

Figure 3 displays the monitored values of CO_2 (June 28th June and September 9th of 2020). Except for the first week of monitoring (between 28/6 and 06/07), the CO_2 values most likely ranged between 500 to 600ppm which is below the defined threshold for residential buildings [27]. However, some peak measurements that reached the level of 700 ppm were also observed. This might suggest that space was significantly under-ventilated and that these parameters may be considered good indicators for early detection of high moisture-related risk probability.

Figure 4 displays the monitored temperature and relative humidity on a psychrometric chart. The intensity of the colour in each band represents the frequency of that value, meaning that the darker is the block, the more often that combination of relative humidity and temperature was measured.
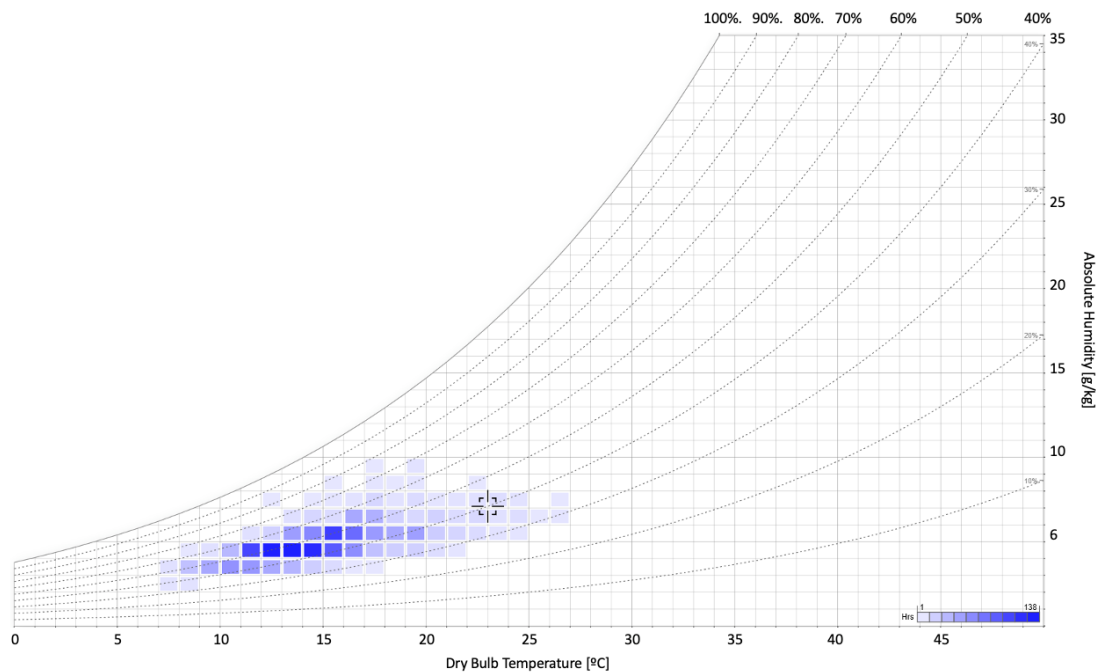
Figure 4: Psychrometric chart with indication of the frequency of values monitored

Figure 4 reveals that the indoor temperature was consistently below 18°C (80% of the time), with peaks lower than 14°C (42% of the time). Despite the indoor relative humidity being for 81% of the time in the optimal range of 40% to 70%, the low temperatures, coupled with cyclical humidity variations and water availability on the surface, favoured mould germination and growth.

4. Conclusions

The investigation shows that the extensive mould infestations may easily go undetected for far too long, which in turn requires significant renovations to completely remove this significant health hazard from damaged premises. Buildings with a high concentration of fungal spores are also more likely to present poor IAQ, high concentrations of particulate matter (PM_{10} and $PM_{2.5}$), as well as a high level of CO_2. This result underlines the importance of building occupants in determining the risk of mould growth, where correct ventilation of indoor space, especially in those cases where high indoor humidity is registered, and access to daylight are essential to mitigate the risks of biological germination and spread. Dwellers are seldom involved in the conversation about how to properly manage the indoor environments and how to assess and evaluate the risks associated with occupancy practices (e.g. ventilation of unoccupied spaces or laundry drying in small and unventilated spaces), despite being strategical and easy-to-change aspects that determine mould growth. This case study also illustrates that when a poor building envelope design overlaps with high relative humidity and temperature, mould growth in interior spaces becomes difficult to suppress for the climate in question. Further, this case study underlines the necessity of developing early detection strategies that could minimize the risk for occupants, as well as reduce the cost of repairs. Finally, findings, even though limited to a case study, further add to call for a change in Australian regulations and

construction practice to address mould at the design stage by establishing a prevention-based approach, rather than remediation.

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