Evaluation of a Polyester Filter and UV Light (PFUV) Dehumidifier to Improve Indoor Environmental Quality: Preliminary Results

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Abstract: Older residential dwellings in New Zealand frequently suffer from poor indoor environmental quality (IEQ) due to an ageing housing stock. Recent New Zealand surveys indicated around 50% of children live in houses that do not meet acceptable standards for thermal comfort. Children in these houses frequently experience respiratory conditions caused by dampness and mould during winter. New regulatory standards requiring a fixed heating source in the main living room of rental houses can increase rents and may result in the heating source not being utilized. This study evaluates an alternative low-cost portable air filter/sterilizer (PFUV) dehumidifier device for improving IEQ within the building envelope using Ultraviolet Germicidal Irradiation (UVGI) and a polyester filter (dual-10 30/30). This paper compares the effectiveness of the PFUV dehumidifier device and a conventional heat pump in terms of measured particulate matters as well as fungal profiles using Potato Dextrose Agar (PDA) plates. The PFUV dehumidifier successfully reduced the relative humidity to within a healthy range of (44–49%) compared to not running the device (54–60%), thereby reducing the suitability of the environment for mould growth. Additionally, the PFUV device achieved a reduction in average particulate matter (PM$_{2.5}$) to within the range of 0.16 to 0.53 µg/m$^3$ compared to the range of 1.06 to 2.42 µg/m$^3$ before using the device.

Keywords: indoor environmental quality (IEQ); ultraviolet germicidal irradiation (UVGI); filter (dual-10 30/30); particulate matter (PM$_{2.5}$); potato dextrose agar (PDA)

1. Introduction

In 2021, a longitudinal study reported by [1] revealed that 50% of New Zealand children sleep in rooms that fall below the expected standard required for thermal comfort during the winter months. This study raised the concerning statistic that out of 2000 children studied, approximately half were found not only to be sleeping in bedrooms that were too cold, as defined by temperatures <19 ºC, but that in many cases, the house temperature dropped to <4 ºC by early morning. Causes for the low temperatures include older insulation and glazing standards followed for residential homes, poor materials, inadequate ventilation, and residents being unable to afford to heat the house. These combined factors result in substandard indoor environmental quality (IEQ) conditions which could cause illness or even death. In 2015, the New Zealand government investigated the death of a two-year-old girl in Auckland who died from a respiratory infection caused by inadequate IEQ conditions of the dwelling in which she lived [2]. One of the major findings was that the dwelling was expensive to heat due to high levels of dampness and low indoor temperatures resulting from the outdated building standards used in constructing the
original dwelling [2]. The New Zealand-based building research organization (BRANZ) [3] survey of 560 houses in New Zealand in 2015 revealed that 47% of these houses did not have insulation of a sufficient standard to abate dampness and maintain adequate indoor temperatures in winter. These issues are likely caused by high relative humidity making rooms difficult to heat due to the humid air having a higher specific heat capacity [4]. As illustrated by the 2015 investigation, such poor IEQ can be harmful to the health of a dwelling’s occupants [5]. An estimated 30,000 children are hospitalized each year for conditions such as asthma and bronchiolitis that are related to poor quality housing [6].

New Zealand statistics show another concerning trend related to increasing dampness and mould in residential houses [7]. As an example, a survey conducted in 2018 showed that 21.5% of New Zealand dwellings were affected by dampness, and 16.9% showed visible mould with a size larger than an A4 sheet of paper [7]. The most common types of mould identified in a survey of New Zealand houses were *Aspergillus/Penicillium, Cladosporium, Chaetomium* and *Stachybotrys chartarum* (the lattermost is commonly known as “black mould” and is highly toxic) [8]. Furthermore, children aged 0–4 and 5–9 living in ‘not owned’ dwellings are more likely to be exposed to mould, with 36% and 38%, respectively, compared to 17% and 18% for owned dwellings, respectively [7]. The surveys also revealed that living in cold, damp, and mouldy houses that are subject to ongoing maintenance resulted in poor overall life satisfaction for children [7]. The data showed that the presence of mould and dampness correlated well with the increased level of asthma, colds, and influenza, which increased the number of sick days taken by occupants [7].

In the humid, subtropical climate of Sydney, Australia, a cohort of five residential dwellings with relative humidity levels above 80% were investigated to categorize remediation approaches to factors contributing to mould growth [9]. The results revealed that remedies to remove mould, such as improvements to ventilation, were insufficient to prevent the reappearance of mould over 12 months, which is a relatively short period. To assess the side effects of mould growth, it was concluded that the interaction of resident behavior and indoor environment parameters based on ISO 13788 and ASHRAE 160 required further investigation [9].

In a global study, Lozano and Siegel (2018) [5] discussed remediation strategies for poor IEQ conditions after reviewing 49 studies addressing social housing mould and dampness conditions compared to private rental residential houses. Their approach focused on cost-effective techniques to achieve healthier dwellings, and the results suggested that this topic requires further investigation and analysis [5].

Mould and dampness in dwellings have been studied widely, and consequently, a range of remedial strategies has been proposed. A promising approach is Ultraviolet germicidal irradiation (UVGI) using a high-efficiency particulate absorbing (HEPA) filter to improve IEQ parameters. UVGI, also known as biocide lighting, was originally introduced to purify indoor air distributed in residential and commercial buildings. The ionizing properties of UVGI work by impeding the replication of microorganism DNA [10–12]. The effect of the UVGI radiation [10,12,13] and irradiance level [13–15] on microorganisms in the infected air depends on the system design. The effectiveness of radiation on infectious agents [16] depends on the microorganism-specific resistance [13]. Gong et al. (2014) [16] reported UVGI being effective against bacteria but that the cellular structure for fungi required more investigation to improve effectiveness, whereas other studies [10,16] have described UVGI as being effective against moulds but more so, generally, against bacteria. Therefore, for treating fungi [17] and Volatile Organic Compounds (VOCs) [18], it is recommended to use UVGI lights in combination with filters of sanitizer titanium dioxide (TiO2), notwithstanding the problem of such filters containing micro-cracks that can shield microbes from UV light [16,17]. The literature [19–27] suggests using HEPA filters (Glass fiber, Polyester and Synthetic/Activated Carbon) to remove dust and microparticles from the air (pollution control) will reduce the growth of those moulds and bacteria that feed on dust. HEPA filters are also known to be energy efficient and have long service lives [19–21].
Regarding microbiological factors, Yassin and Almouqatea (2010) [28] performed an assessment of airborne mould and bacterial growth in a residential dwelling using culture-based techniques that evaluated colonial characteristics based on colour and turbidity. A key finding from the study was that bacterial counts can increase more rapidly than moulds, with 55% and 25%, respectively. Therefore, it is important to understand the relationship between IEQ parameters and ventilation experimentally. This was examined by Rim and Novoselac (2010) [29], who demonstrated that the removal of indoor airborne bacteria and mould is correlated with its dilution and removal by fresh air supplied through the ventilation system. To achieve this, consideration of parameters, such as source location, the variation in the indoor airflow patterns, and the particle size, need to be considered [27,30]. Therefore, in our study, it was considered important to understand the level and nature of the particulate matter in the region under investigation. Each year Land Air Water Aotearoa (LAWA) publishes average outdoor values for particulate matter (PM$_{2.5}$ and PM$_{10}$), including associated data for temperature and relative humidity [31]. Average annual and highest daily averages (PM$_{2.5}$, PM$_{10}$, T $^\circ C$, %RH) for Hamilton (Waikato region) showed that the city exceeded the maximum level guideline twice (in 2019 and 2020), as shown in Table 1.

Table 1. The Land Air Water Aotearoa (LAWA) data for Hamilton and Auckland for a 3-year period (adapted from [31]).

| Town   | Year | PM$_{10}$ µg/m$^3$ | PM$_{2.5}$ µg/m$^3$ | Level | PM$_{10}$ µg/m$^3$ | PM$_{2.5}$ µg/m$^3$ | Level | Temperature and Relative Humidity $^\circ C/%$RH |
|--------|------|--------------------|---------------------|-------|--------------------|---------------------|-------|---------------------------------------------|
|        |      | Annual Average     | Highest Daily Average |       | High               | Low                 | Average |
|        |      |                    |                     |       |                   |                     |        |
| Hamilton | 2018 | 32.1               | 22.9                | U     | 43.2              | 30.2              | U       | 16/100                                       | 3/45  | 11/85                                       |
|        | 2019 | 48                 | 40.5                | E*    | 48                | 40.5              | E*      | 18/100                                       | 5/51  | 12/81                                       |
|        | 2020 | 43.2               | 30.2                | E*    | 32.1              | 22.9              | U       | 18/98                                        | 2/44  | 11/81                                       |
| Auckland | 2018 | 15.4               | 6.8                 | U     | 99.4              | 64                | E*      | 18/100                                       | 4/55  | 12/88                                       |
|        | 2019 | 16.7               | 7.2                 | U     | 33.2              | 13                | E*      | 18/100                                       | 3/48  | 12/84                                       |

U: Under the limit of the guidelines and E*: exceeded the guidelines based on Land Air Water Aotearoa.

The factors discussed above were instrumental in the New Zealand government mandating that landlords install heat pumps in the living area of rental properties from the 1 July 2021 [32]. This move was part of a nationwide strategy to achieve ‘Healthy Home’ standards [32] in residential rental dwellings. However, the effectiveness of this regulation is still not clear. One unforeseen consequence is the negative impact on the national electricity supply, as occurred on the 9th of August 2021 when the country reached very low temperatures and electricity demand soared, leading to temporary blackouts for thousands of homes on the coldest night of the year [33]. Additionally, as electric vehicles become more commonplace, higher demand for electricity in the evening will also coincide with higher electricity consumption in recharging car batteries, so this kind of event may increase in frequency in the near future without significant additional investment in the electrical grid. Another factor is that the increased costs of installing and running heat-pumps impacts the affordability of rental properties occupied by low income-earners, as well as their ability to pay for running the machines during periods when they are needed.

From the literature and our previous research [22–33], we could not determine a link between using a heat source to eliminate the growth of mould in residential dwellings in New Zealand during the coldest months in winter. However, the New Zealand government emphasises the use of heat pumps as part of the Healthy Home Standards as a solution. Separate findings by the Landcare Research NZ Fungi databases describe New Zealand houses as having the highest levels of mould and bacteria compared to worldwide figures [34,35]. Therefore, the aim of our study was to examine the effectiveness of a PFUV
dehumidifier device in reducing mould populations in a bedroom with no heat source and compare this with a bedroom that contained a heat pump. Both rooms were in active use in an occupied house, and measurements were taken during the winter period (June and July) in Waikato, New Zealand. Therefore, the results reflect field data due to traffic by the household occupants in both rooms. The investigation also assessed thermal comfort parameters ($T$, °C and %RH) and particulate matter concentration ($PM_{2.5}$) for both the test rooms and outdoor conditions. For microbiological assessment, potato dextrose agar (PDA) was used to determine levels of mould elimination in both bedrooms. PDA (BAM Media M127), made from potato infusion and dextrose, is the most widely used medium for growing mould [36]. Such assessments assisted in quantifying and evaluating the viable airborne mould reduction whilst using PFUV dehumidifier and heat pumps. This paper extends the work from our previous study [20] by performing a microbiological assessment of mould growth to gain counts and identify species. It also includes data points for the morning to compare with the evening measurements. This paper also compares the performance of our prototype device to that of a commercially available heat pump in occupied rooms.

2. Materials and Methods

2.1. Test Location

The experimental setup was performed in a residential dwelling with a floor area of 270 m$^2$ located in north Waikato (37 km to the main regional city Hamilton), New Zealand. This dwelling was built in 1985 with old building standards using a concrete slab floor and included two bathrooms and four bedrooms. The exterior wall materials were made using single skin brick with brick cavity-on-timber wall framing, with small areas of fibre cement-based sheet cladding on the framing. The roof was composed (with old blown-in fibre insulation) of pressed metal roof tiles with stone chip coating attached to timber roof trusses and a frame made of aluminum [20]. In this study, we sought to investigate mould growth in two of the bedrooms, in which occupants (two children and two adults) experienced dampness and discomfort during the night. Both bedrooms (bedroom 2-BR2 and bedroom 3-BR3) were west-facing, as shown in Figure 1a. The small internal roof gutter and internal roof gutter outlet on the west side of the hallway have two issues, as shown in Figure 1b, which are affected by the heavy rainfall and leaks into the wall cavity if this gutter is overloaded or blocked by leaves. Therefore, both bedrooms experience high relative humidity and low temperature readings during June, July and August with “crying windows”, as shown in Figure 1c. The two months (June and July) had recently experienced very low temperatures and foggy conditions, as illustrated in Figure 1d. Historically, June and July are the coldest months in Waikato, with an average high value of 14.0 °C and 13.8 °C, respectively, and corresponding low values of 5.1 °C and 4.0 °C, respectively. Average relative humidity was 79% for June and 90.8% for July, whilst there was 113 mm of rain in June and 118.2 mm of rainfall in July [37].

2.2. Experimental Setup

In this study, we investigated and compared the effectiveness of using a PFUV dehumidifier device (placed in bedroom 3 (BR3)) with a Mitsubishi Electric heat pump 3.2 kW EcoCore R32 (installed in bedroom 2 (BR2)) over the period 6 July to 20 July (14 consecutive days). Before and during the study days (18 June–20 July—33 consecutive days), an air image sensor was placed in each bedroom to monitor the IEQ parameters: $PM_{2.5}$, $T$ and %RH, as shown in Figure 2. The Camfil air image sensors #1 and #2 are manufactured by Camfil AB, Stockholm, Sweden, with a purchased cost of NZ$860. The sensors were placed in each bedroom, as shown in Figure 2. Each sensor weighs 200 g with dimensions of 144 × 64 × 61 mm. It operates with voltage (5V/DC) and consumes 10 W. The accuracy of the Camfil sensor for measuring particulate matters ($PM_{2.5}$) is ±0.1 µg/m$^3$ in the operating range of 1 to 2.5 µg/m$^3$; ±0.5 °C for air temperature with an operating range of −10 to +50 °C; and ±2.5% for relative humidity with an operating range of 0 to 100% non-condensing.
Figure 1. (a) Test bedrooms (BR2 and BR3), (b) the gutter structure, (c) the indoor window for bedroom 3 (close to the gutter), and (d) a typically foggy day in Waikato during July.

Figure 2. Schematic diagram (iso-view) for Bedrooms 2 (BR2) and 3 (BR3) showing the Heat Pump, PFUV dehumidifier device, and the Air Image Sensor locations (#1 and #2). The location of the microbial monitoring plates 1, 2 and 3 are also indicated for each bedroom.

During the experimental design, three locations of interest were selected to place the Petri dishes containing potato dextrose agar (PDA). These are shown as the yellow circles
as in Figure 2. Location “1” was close to the bed (height 0.6 m), Location “2” was in the corner of the bedroom (height 0.8 m) next to the sensor and location “3” was (height 0.0 m) close to the window.

The PFUV dehumidifier is a retrofitted dehumidifier converted from a DB48WH-NZGC model, with a fan flow rate of 0.018 m$^3$/s using R-134a refrigerant (which is not banned in New Zealand). The modification involved adding Ultraviolet Germicidal Irradiation (UVGI) lights [38,39], using 8 W germicidal fluorescent T5 (UV) lights of 16 mm diameter tube, 300 mm length, UV-C radiation output of 2.4 W, 254 nanometres (nm) wavelength and lifetime 9000 h, and a high-quality polyester filter (Dual-10 30/30), as shown in Figure 3. This filter operates with an efficient energy consumption and long service life aligned with ASHRAE MERV 8 [20,40]. The polyester filter allows an airflow of 0.472 m$^3$/s and operates with a 70 °C maximum temperature and 100% relative humidity.

In 2020, this device was tested in a single office bedroom and showed promising results in reducing dampness readings and increasing the room temperature during low outdoor temperatures (below 7 °C). The heat generated from the device was released by its coil, which is used to condense water vapour from in-drawn air [20]. The PFUV dehumidifier (as shown in Figure 3) was created by modifying an existing dehumidifier to include air purification. Two 8 W germicidal fluorescent T5 UV lights and the dual-10 30/30 filter were added in order to, respectively, denature airborne microbes and filter most particulate matters from the air. The retrofitted dehumidifier was a DB48WH-NZGC model, with a 240 W power output, and fan flow rate of 0.018 m$^3$/s using R-134a refrigerant. It should be noted that this refrigeration is being phased out in New Zealand, meaning that new devices will not be built using it; however, existing devices may still use it. Moreover, the refrigerant type makes no difference to the operation of the device that we are repurposing. It is part of a closed condensation system that we did not modify. The dual-10 30/30 filter was made of polyester based on ASHRAE MERV 8, allowing an airflow of 0.472 m$^3$/s and operating with a 70 °C maximum temperature and 100% relative humidity.

During the experimental period (18 June–20 July), the outdoor parameters of the following were measured: PM$_{2.5}$, temperature dew point (TDP), $T_{\text{outdoor}}$, $T_{\text{max}}$, $T_{\text{min}}$, and %RH at 07:00 and 19:00 using a dust air quality sensor (TERA NextPM optical Sensor manufactured in France) with the following parameters: measuring range: 0–1000 µg/m$^3$, repeatability: <3%, size detection range: 0.3–10 µm, operating temperature +70 °C to −2 °C, communication protocol: UART/Modbus, power supply: 5.0 VDC, weight 45 g, sensor dimensions 61.85 × 52.55 × 23.72 mm. As described above, the indoor air parameters were
measured using two Camfil air image sensors. Camfil New Zealand calibrates the Camfil sensor to work with New Zealand ambient parameters.

Based on the literature [1–3,6,7], we were particularly interested in analysing the data during the daily periods of 19:00–7:00 (the average for a child’s bedtime in New Zealand [1]). During that time, all windows to the outside were sealed, and internal doors were closed in both BR2 (heat source: heat pump) and BR3 (no heat or ventilation source).

The data collected from the 18 June to the 6 July showed high relative humidity readings during the 18, 22, 23 June, and 2, 3 and 4 July (time of interest: 19:00 to 7:00 next day) in BR3 (no heat source or ventilation) compared to BR2 (with heat pump operating during that time), as shown in Figure 4. With respect to particulate matter such as dust, air image sensors recorded PM\(_{2.5}\) for both BR2 and BR3 (Figure 5) during the same period. These sampling periods were chosen based on literature recommendations to investigate indoor parameters when the outdoor temperature is below 7 \(\degree\)C. Based on Figures 4 and 5, the RH readings suggested that both bedrooms may be subject to mould growth, especially as higher PM\(_{2.5}\) readings are associated with mould growth and spread (RH of 50% or above) because dust provides an organic food source for moulds. To reduce (and ideally eliminate) mould, there is a need to reduce relative humidity to 30–48% and reduce dust concentration in both bedrooms. The collected temperature data have not been presented as they are all in the range of 0 to 50 \(\degree\)C; however, the temperature behavior will be reported when the PFUV dehumidifier device is evaluated to ensure no thermal comfort differences arise between the devices.

The outdoor conditions for the night of 18/19 June were PM\(_{2.5}\) = 1.5 µg/m\(^3\), \(T = 8 \degree\)C and RH = 80%, and for the morning period, PM\(_{2.5}\) = 1.53 µg/m\(^3\), \(T = 12 \degree\)C and RH = 96%. Compared to the indoor conditions, Figure 4a, we found that BR2, with the heat pump set to 21 \(\degree\)C, was associated with relative humidity dropping from 62% to 52% (this drop occurred due to the heat pump being in operation, whereas there was no device in BR3). The PM\(_{2.5}\) values were lower than those in BR3, as shown in Figure 5a. For the 22/23 June, the outdoor night period readings were PM\(_{2.5}\) = 3.53 µg/m\(^3\), \(T = 8 \degree\)C and RH = 77%, and the morning period readings were PM\(_{2.5}\) = 3.26 µg/m\(^3\), \(T = 3 \degree\)C and RH = 93%. However, Figures 4b and 5b for indoor conditions show a close outcome to Figures 4a and 5a.

For the 23/24 June, the outdoor night period readings were PM\(_{2.5}\) = 3.4 µg/m\(^3\), \(T = 7 \degree\)C and RH = 64%, and the morning period readings were PM\(_{2.5}\) = 6.27 µg/m\(^3\), \(T = 2 \degree\)C and RH = 93%. Figures 4c and 5c show small differences in relative humidity and PM\(_{2.5}\) for both bedrooms.

For the 2/3 July, the outdoor data for the evening period were PM\(_{2.5}\) = 1.55 µg/m\(^3\), \(T = 13 \degree\)C and RH = 64%, and the morning period values were PM\(_{2.5}\) = 3.44 µg/m\(^3\), \(T = 2 \degree\)C and RH = 86%. Figures 4d and 5d show a close trend for relative humidity and PM\(_{2.5}\) in both bedrooms.

For the 3/4 July, the outdoor data for the evening period were PM\(_{2.5}\) = 3.54 µg/m\(^3\), \(T = 4 \degree\)C and RH = 91%, and the morning period data were PM\(_{2.5}\) = 6.06 µg/m\(^3\), \(T = 1 \degree\)C and RH = 95%. Figures 4e and 5e again show a close trend for relative humidity and PM\(_{2.5}\) in both bedrooms.

For the 4/5 July, the outdoor data for the evening period were PM\(_{2.5}\) = 4.79 µg/m\(^3\), \(T = 4 \degree\)C and RH = 89%, and the morning period values were PM\(_{2.5}\) = 5.89 µg/m\(^3\), \(T = 1 \degree\)C and RH = 92%. Figures 4f and 5f again show a close trend for relative humidity and PM\(_{2.5}\) in both bedrooms. The particulate matter readings were high on the 4/5 July, as shown in Figure 5f, due to the human activity around the bedrooms (at the weekend).
From Figures 4 and 5, it is clear that BR3 experiences a higher humidity environment and slightly higher levels of particulate matter, which could result in mould growth. The source of the humidity may be associated with poor gutter maintenance indicated in Figure 1a. However, BR2, which returned acceptable readings of relative humidity and particulate matter, may also harbour mould growth based on moisture levels physically evidenced in Figure 1c by the “crying windows” factor. Therefore, in this study, airborne mould population assessments were made for both bedrooms. As indicated in Section 1, the airborne assessment was performed using potato dextrose agar (PDA) plates.
2.3. Test Method

Our findings demonstrated that the heat pump in BR2 was not effective at reducing moisture, as indicated by the presence of “crying windows” every morning caused by condensation. Effectively, we were able to use BR2 as a moisture control bedroom for BR3. We performed a biological assessment of BR2 and BR3 using Petri dishes with PDA to assess the colonies of mould growth before and after operating the PFUV dehumidifier in BR3 and heat pump in BR2. Furthermore, the air image sensors captured live data in both BR2 and BR3.

Microbiological testing was performed on the 11 and 13 July. A total of 36 PDA and plates were used, representing three sites tested in each of the two rooms (see Figure 2) for

Figure 5. Particulate matter (PM$_{2.5}$) readings for the period from 19:00 to 7:00 the following day for the (a) 18, (b) 22, (c) 23 June and (d) 2, (e) 3 and (f) 4 July when the outdoor temperature $< 7 \, ^\circ$C.
the evenings and mornings of the three dates given above. In addition, one unexposed control plate was processed for each media type to confirm batch sterility. Data were collected and processed as indicated in the flow chart illustrated in Figure 6.

![Flow chart](image)

**Figure 6.** Flow chart for the data collected from the 18 June until the 20 July and the microbiological testing schedule 11 July 2021, and the repetition of the experiments on the 13 July.

For the experimental testing on 11 and 13 July, as shown in Figure 6, at 9:00, the curtains were opened in both BR2 and BR3, and the windows and doors were kept closed as the following were performed:

1. One set (comprising 1 × PDA plate) of agar plates was positioned at each of the three locations in each of BR2 and BR3, as indicated in Figure 2. The lids were removed, and the surface of the plates was exposed to the air for three hours (9.00–12.00).
2. Camfil air image sensors recorded the PM$_{2.5}$ (µg/m$^3$), temperature (°C) and relative humidity (%RH) for both bedrooms.
3. Simultaneously, the TERA NextPM sensor measured the outdoor conditions (PM$_{2.5}$ (µg/m$^3$); temperature (°C) and relative humidity (%RH).
4. At 12:00, the lids were replaced on the agar plates, and the plates were removed from the rooms and incubated at 24 °C for 5 days to allow colony formation and enumeration.

The two rooms were again evaluated in the evening following this treatment after both bedrooms had benefitted from the day’s solar radiation. The second phase of the experiment started at 21:00 by switching on the heat pump (21 °C) in BR2 and the PFUV dehumidifier device in BR3. After a further three hours of plate exposure (i.e., at 23:59), the agar plates were again collected and sent to the laboratory for analysis. The experimental procedure was repeated on the 13 July to further validate the effectiveness of the PFUV dehumidifier device and compare it to the heat pump with respect to improving the indoor environmental parameters and assessing the reduction in mould.

3. Results and Discussion

This section presents and discusses the data captured for the 11 and 13 July when the heat pump was running in BR2 and the PFUV dehumidifier in BR3. It is likely that
solar radiation impacted positively on the house’s IEQ during the morning and afternoon. Therefore, the air image sensor data captured from 9:00 to 23:59 will be discussed to demonstrate the behavior of both BR2 and BR3 during the experimental work.

3.1. Air Image Sensor Data

Part of maintaining a healthy IEQ involves addressing relative humidity. In countries such as New Zealand, where the relative humidity is generally high, and a significant amount of the housing stock has been characterized as “old, cold and damp” [41], achieving reduced relative humidity, along with heating (improved thermal comfort), and reduced particulate matters, are the goals. Damp houses are associated with respiratory problems, and damp air is harder to heat. Houses with higher particulate matter, including mould spores, are also associated with respiratory problems.

We used air image sensors during the experiment to monitor the IAQ parameters such as relative humidity and PM$_{2.5}$ whilst the heat pump was run in BR2 and the PFUV dehumidifier was run in BR3. Figure 7 shows the %RH data for both bedrooms from 19:00 to 7:00. There was a significant improvement in the curves of the %RH compared to Figure 4. During that time, the PFUV dehumidifier managed to drop the %RH within the range of 44% to 49% compared to not running the device, where a higher range of 54.85% to 60.21% was measured. The heat pump’s average %RH reading was slightly higher during the experiment, from 48.46% to 57%.

![Figure 7. Relative Humidity readings for the period from 19:00 to 7:00 the following day for the (a) 6, (b) 7, (c) 8 and (d) 9 July.](image)

Reducing the PM$_{2.5}$ counts aligns with ASHRAE 62.1, 2019 [42] and is also desirable from the point of view of reducing the nutritional medium for mould growth. Reducing relative humidity to below 50% also reduces the necessary hydration for effective mould growth. Given the temperature must be suitable for the thermal comfort of the room’s
occupants, the device’s best functions are to reduce the relative humidity so that it does not fluctuate much above 50% and reduce the nutritional media (particulate matters) available for the mould. As shown in Figure 6, we ran the PFUV dehumidifier in BR3 from the 6 to the 20 July to assess and compare the outcomes against running the heat pump in BR2. Figure 7 highlights that the PFUV device reduced the RH% to between 44% and 49%, at average temperatures between 18.07% and 19.14 °C, thereby achieving the desired drop in %RH of below 50% in BR3 whilst maintaining thermal comfort. The PM$_{2.5}$ data presented in Figure 8 show that the average of the PM$_{2.5}$ using PFUV was 0.16–0.53 µg/m$^3$, which is an improvement compared to the data measured before using the device 1.06–2.42 µg/m$^3$. Meanwhile, the PM$_{2.5}$ data in the room with the Heat Pump were 0.76–2.18 µg/m$^3$. Therefore, the filter used in the PFUV dehumidifier device is effective in reducing the particulate matter count, which, combined with dehumidification of the air, reduces the favourable conditions for mould growth.

![Figure 8. Particulate matter (PM$_{2.5}$) readings for the period from 19:00 to 7:00 the following day for the (a) 6, (b) 7, (c) 8 and (d) 9 July.](image)

3.2. The Indoor Environmental Quality (IEQ) Data

The IEQ parameters of BR2 (heat pump) and BR3 (PFUV dehumidifier device) were compared. Figure 6 shows the indoor particulate matter (PM$_{2.5}$), air temperature (T °C) and relative humidity (%RH) in both bedrooms from 09:00 to 23:59 on the 11 and 13 July. These data are also shown in tabular form during the full period on those dates. For the 11 July morning period, the outdoor average values were T = 7 °C, RH = 84% and PM$_{2.5}$ = 3.36 µg/m$^3$, as shown in Figure 9a. The corresponding indoor average values for BR2 were T = 19.67 °C, RH = 52.36% and PM$_{2.5}$ = 1.16 µg/m$^3$; and for BR3, were T = 17.14 °C, RH = 50.03% and PM$_{2.5}$ = 1.19 µg/m$^3$, which showed that BR3 had lower humidity and lower temperature compared to BR2. During the period from 12:00–21:00, the BR2 average readings were T = 20.64 °C, RH = 54.79% and PM$_{2.5}$ = 2.14 µg/m$^3$, and for BR3, T = 18.56 °C, RH = 52.13%
and PM$_{2.5}$ = 1.73 µg/m$^3$, which indicated that BR3 still had lower humidity and less particulate matter compared with BR2. In the evening period from 21:00–23:59, with the heat pump operating from 19:00, average values for BR2 were $T = 22.33$ °C, RH = 49.66% and PM$_{2.5}$ = 1.44 µg/m$^3$. However, for BR3 with the PFUV dehumidifier device operating from 19:00, the values were $T = 17.93$ °C, RH = 47.30% and PM$_{2.5}$ = 1.07 µg/m$^3$, which indicated that the dehumidifier reduced the relative humidity and the polyester filter influenced PM$_{2.5}$ concentrations.

Figure 9. The indoor environmental quality data for the period from 9:00 to 23:59 (a) for the 11 July and (b) for the 13 July.

Figure 9b shows the 13 July data (T, RH and PM$_{2.5}$) for both BR2 and BR3 from morning until evening (9:00–23:59). Although on that day, the minimum outdoor temperature reached −1 °C, the average temperature differences between both bedrooms were as
follows: 2.85 °C for the morning period; 1.32 °C for the afternoon period; and 4.35 °C for the evening period. At the same time, the difference in the absolute humidity between BR2 and BR3 during the evening period was 2.0265 (g/kg) dry air.

Therefore, the results showed that on the 11 July, when the outdoor relative humidity was 66%, there was a reduction in the relative humidity of BR3 during the evening period from 53% to 46%, and for BR2, this reduction was from 49% to 47%. The resulting difference between indoor and outdoor relative humidity was 17% and 14% for BR3 and BR2, respectively.

Comparing this to the 13 July, when the outdoor RH condition was 82% and the temperature fell below 0 °C, the PFUV dehumidifier device dropped RH in BR3 from 52% to 47%, whereas in BR2, it dropped from 48% to 47% for the evening period, as shown in Figure 9b. This reduction was clear on the 11 and 13 July in BR3, with RH dropping by 7% and 5%, respectively, during the operation of the PFUV dehumidifier device. The resulting difference between indoor and outdoor relative humidity was 32% for both BR3 and BR2.

The PM$_{2.5}$ values were similar, although lower readings were observed in BR3 during the evening. This occurred when the evening outdoor temperature was 14 °C warmer than the 13 July reading. Figure 6 indicates that the PFUV dehumidifier device can better reduce the PM$_{2.5}$ compared to the heat pump over a wide range of external temperatures as on the 13 July in BR3. PM$_{2.5}$ was reduced by 1.08 µg/m$^3$ compared to an increase of 0.18 µg/m$^3$ in BR2 during the evening period.

The results of using the PFUV dehumidifier device showed that the relative humidity reading improved in BR3 and that the operation of the PFUV dehumidifier device brought the RH down to the same level as that in BR2 (in which the heat pump operates). Although relative humidity contributes to the growth of mould colonies, it is not sufficient to say that this reduction in relative humidity will have reduced the colony counts in the room. Therefore, the next section investigates the impact of the PFUV dehumidifier device and the heat pump on mould elimination in both bedrooms.

### 3.3. Mould Assessment

A key indicator of indoor air quality is the microbial population present, which tends to consist of moulds that can thrive in buildings that have high relative humidity [20].

In this section, the effect on bedroom mould populations when treating the air with a PFUV dehumidifier device was investigated and compared to treatment with a heat pump. Settle plates were used to record counts in each of BR2 and BR3 following the experimental setup. Potato dextrose agar (PDA) was purchased (Fort Richard Laboratories, Otahuhu, NZ) and used for enumerating mould colonies. One plate of PDA agar was placed at three different locations in each bedroom (see Figure 2). Plate lids were then removed, and the surface of the agar was exposed to the air for three hours (9:00–12:00). A process for dehumidifying and filtering the air (PFUV dehumidifier) was then performed and the room was re-assessed using fresh settle plates (21:00–23:59) on the same day. The entire process was repeated twice over a total of two days. Exposed plates, and unexposed control plates, were incubated aerobically at 24 °C for up to five days and colonies were counted. Spores of fungal colonies of interest were examined microscopically (standard light microscope), using wet tape mounts in lactophenol cotton blue stain and 400× magnification, as shown in Figure 10. Figure 10 shows three different microscope examples of observed moulds. Figure 10a shows a presumptive *Cladosporium*. Figure 10b shows a presumptive *Penicillium*, which is typical of the green-centered/white-rimmed colonies. Figure 10c shows a presumptive *Mucor* strain, which is typical of the smaller brown colonies seen mixed in with the green colonies in Figure 10.
Figure 10. Microscopic photos for the mould/fungi found in both bedrooms. Presumptive identification was based on spore morphology (a) Cladosporium, (b) Penicillium and (c) Mucor.

Mould populations were counted separately based on colonial morphology, as shown in Figure 11, which shows the agar plates used in this study to assess mould growth before and during the use of the heat pump in BR2 and PFUV dehumidifier in BR3. Figure 11 shows the elimination of moulds on the 11 and the 13 July at the three different room locations tested. The PFUV dehumidifier shows a large impact on reducing the mould colonies at locations 1 and 2 on the 11 and 13 July (as shown in Figure 2). However, in location 3, which is close to the window, the reduction was not as marked, possibly because it is too close to the main sources of water build-up, as shown in Figure 1b. It is possible that location 3, being adjacent to the external window, could measure outdoor mould concentrations. However, since the window was sealed for the duration of the experiment, this contamination from outdoor mould sources should be low. However, future work will measure the outdoor mould concentration and the inflow of outdoor air into each room to control for this variable.

Based on the airborne assessment, it is clear there is a reduction in the overall colony count at locations 1 and 2 in BR3 for the morning and evening period, as measured in the PDA agar. However, the effect is less pronounced for location 3, which is close to the window, which suffers from water condensation, as shown in Figure 12d. When comparing mould growth for the morning and evening periods for both bedrooms (as shown in Figure 11), it is clear that outdoor humidity, which is in excess of indoor humidity in both bedrooms, impacts the amount of mould growth. Furthermore, the heat pump in BR2 was not able to reduce the numbers compared to BR3, which showed low mould counts at the three locations based on the assessment of the PDA Petri dishes, as shown in Figure 12. The effectiveness of the PFUV dehumidifier was clear for eliminating mould growth from the morning to the evening period on the 11 July, achieving a reduction of between 94% and 98% at locations 1 and 2 but 33% at location 3; and on the 13 July, there was a reduction of between 44% and 68%, as shown in Figure 12c,d. In general, BR3 suffered from a high colony count for mould, as shown for the morning period in Figure 12c. The significant improvement is visible when comparing Figure 12c,d.

Ideally the problem of poor-quality housing would be addressed at the structural level, by building better quality homes or modifying existing houses to meet better housing standards; however, addressing the supply issue takes many years. New Zealand, like many countries, suffers from an insufficient supply of housing to meet the demand of growing populations in large cities [43,44] and is affected by building material supply-chain issues that have been exacerbated by the COVID-19 pandemic [45]. Therefore, this paper explored a mitigation approach, discussing a low-cost solution to reduce mould by reducing the favourable conditions for mould growth and improving thermal comfort, whilst taking the built environment as given, as would be the case for most households of modest means.
Figure 11. The PDA agar plate samples for BR2 and BR3. (a) 11 July and (b) 13 July.
Figure 12. The LOG10 mould counts collected using the PDA agar (a) BR2-Morning period, (b) BR2-Evening period, (c) BR3-Morning period and (d) BR3-Evening period.

4. Conclusions

Dust and humidity provide ideal environments for the growth of moulds. Previous research suggests that UV and heat pumps alone cannot deliver the levels of microbial control required to provide healthy environments in older residential dwellings. This view is supported by the results of this study, where we demonstrated that the building envelope was not able to cope with dampness issues and related mould growth using a heat pump alone. We showed that a low-cost dual 10 30/30 polyester HEPA filter in combination with UV irradiation (PFUV dehumidifier) can significantly lower the levels of particulate matter, including moulds, in a bedroom of an older house, particularly when compared to a room treated using a heat-pump. Further work will be required to examine the impact of active use of the rooms, and the next segment of this project involves investigating the impact of the devices without occupation. This work will take place on the same dates as the work described in this study but will remove the effect of having occupants making use of the rooms.
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