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Prototyping a low-cost residential air quality device using ultraviolet germicidal irradiation (UVGI) light

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ABSTRACT

Many New Zealand residential dwellings suffer from dampness and fungi during the winter, which can cause respiratory health problems. This can be due to poor insulation and ventilation, and the situation worsens when residents cannot afford to heat the dwelling. The main aim of this paper is to modify an existing dehumidifier so that it can remove moisture, heat the living space and reduce fungi growth and bacteria. To achieve that, we installed ultraviolet germicidal lights (UVGI) in an existing dehumidifier with a total cost of USD $150.7 (NZD $213.76). The UVGI lights are known to be efficient in destroying the DNA of fungi and bacteria. The results show that the device reduced the fungi growth and did increase the room temperature because the dehumidifier captured two litres of water over 24 h of testing. The proposed device did achieve a reduction in particulate matters, from 0.9 $\mu g/m^3$ to 0.14 $\mu g/m^3$ and an acceptable range of relative humidity below 50%, which reduces the favourable conditions for fungi growth. Therefore, our proposed low-cost device does improve the indoor air quality (IAQ) in the living space.

Specifications table

Hardware name	*Dehumidifier with UVGI light (UVGID)*
Subject area	• Engineering and Material Science • Biological Sciences • Environmental
Hardware type	• Mechanical engineering and materials science • *Other [Indoor Air Quality]*
Open Source License	• TAPR OHL
Cost of Hardware	• USD $150.7 (NZD $213.76)
Source File Repository	https://doi.org/10.17632/bshhwy3czd.2

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Hardware in context

Air quality improvement systems play a vital role in a healthy built environment. Damp houses are harder to heat and more likely to lead to respiratory and other health problems. One of the components of a healthy living space is effective climate control. In New Zealand, units are available to perform different tasks as shown in Table 1 [1]: heat, cool, dehumidify and purify, but they often involve a significant upfront cost to buy, especially those that do more than one task, and have high running costs. Moreover, systems that perform air purification are generally designed to remove only heavy particles from the air (such as dust). A few devices have been designed to remove pathogens, which are the cause of diseases. Devices with germicidal functions are mainly effective on bacteria and are generally ineffective against viruses.

A significant issue for New Zealand households is the poor indoor air quality (IAQ) which is caused by a combination of low temperatures, high humidity and the presence of many fungi spores and pathogens in the air. These can be detrimental to the health within the living space [2]. Overcrowding, which is common in lower income homes in areas with higher median rents, only makes this situation worse. This is especially problematic because lower income families are unable to afford the means to improve the IAQ. This is because good insulation, air conditioning units, heaters and dehumidifiers are all expensive to purchase, as is the cost of operating. Housing provided by the New Zealand government also frequently suffer from poor IAQ, exacerbated by the fact that residents are unable to afford to heat them [1].

A previous study [3] shows that comfort is one measure of well-being as it is related to the satisfaction with the indoor living environment. Lu et al. [4] explored a way to supply additional air into a kitchen while cooking to reduce the high temperature and gas concentrations using an air curtain supply system. Another study [5] indicates that significant changes to the IAQ environment resulted in reducing energy consumption and that improving the indoor climate minimises the risk of fungi growth. Liu et al. [6] investigated the methods computationally to enhance the living and sleeping of human beings using an air conditioning system to maintain a comfortable IAQ environment. However, [6] focuses on the energy utilisation improvement for IAQ without addressing the indoor air parameters.

Recently, several studies [1,7–10] examined experimentally and mathematically the use of Ultraviolet germicidal irradiation (UVGI) lights embedded within indoor climate control devices for the purpose of reducing the transmission of airborne infections. For example, [7] embedded UVGI in a building's HVAC system and measured the resultant air quality. They concluded, however, that further testing was required. Other literature [8–10] suggested alternative methods of installing the UVGI components and investigated the effects of lamp quality and exposure time in residential dwellings with a view to their impact on the occupants' safety.

Recently studies have investigated different methods to improve IAQ focusing on the COVID-19 pandemic, such as using dehumidifiers [11], UVGI lights for airborne bioaerosol disinfection in HVAC ducts [12], low-cost sensors to detect common indoor pollutants [13 14 15] and numerical models for ultraviolet photocatalytic oxidation (UV-PCO) to eliminate volatile organic compounds (VOCs) [16]. It is also possible to use an IAQ device's by-product for pathogen detection: Moitra et. al [11] showed that dehumidifier condensate can be used to detect the SARS-CoV-2 virus. Dehumidifiers placed in crowded areas such gyms, restaurants, hospitals, dance clubs and health care facilities could have their condensate trays assessed for SARS-CoV-2, offering a simple and low cost testing method suitable for high-traffic areas.

Based on the literature gap, we develop and construct an indoor air quality improvement system which can dehumidify, purify, and control the temperature of the air (using the coil of the dehumidifier). The unit is economical to run and maintain while being relatively cheap to produce. This is done by repurposing a household dehumidifier and moving the working components to a larger enclosure. These are then combined with germicidal irradiation technology such as UVGI lights to reduce and eliminate fungi spores and bacteria, thereby improving the (IAQ) for the selected living space.

The unit was designed to meet the following requirements:

- Low cost to construct and run
- Use readily available standard components
- A portable standalone unit
- Ability to dehumidify and purify air

Table 1
Prices for New Zealand commercially indoor climate control devices [1].

Device Type	Purchase cost (approx. $NZ)	Running cost (approx. $NZ/kWh)	Functionality
Electric resistance heater	$20-$250	0.26	Heating
Dehumidifier	100–300	0.21–1.42	Dehumidification
Gas heater	1,000–2,700	0.15–0.26	Heating
Air purifier	100–900	0.03–0.59	Purification, Heating, Cooling,
Heat pump	1,500–3,500	0.08	Heating, Cooling, Dehumidification Cooling

Hardware description.

The IAQ system comprises two main modules.

1. A dehumidifier manufactured by General Electric Company Limited (GEC Ltd.) Model (DB48WH-NZGC) which is repurposed and the base and enclosure modified to accommodate the second module.
2. UVGI lights (Philips UV-C) complete with T5 battens and ballasts (Tridonic).

The purposes of our design and prototype of an IAQ improvement device are as follows: (i) Humidity reduction. A household dehumidifier is repurposed using the necessary system components, such as a tower, fan, evaporator, condenser, switches, reservoir, and wheels. (ii) Air purification. We use ultraviolet germicidal irradiation technology to remove fungi spores and bacteria from the air. To achieve that, we used two UVGI-C fluorescent tubes powered by two electronic ballasts. The switch for the lights is on a separate circuit from the dehumidifier power, allowing the unit to be run without the UVGI lights if required. (iii) Increase the air temperature.

The modern dehumidifier process passes air through the evaporator which cools the air to below the dewpoint and then to the condenser, causing the air to be reheated once the evaporator has removed the water. Since water has a higher specific heat capacity (4200 kJ/kg°K) than air (718 kJ/kg°K), dry air takes less energy to heat than air with a high moisture content, resulting in more efficient heating after the dehumidification. A similar process occurs in the dehumidifier used in our study; however, it may not be as effective as modern units as the air first flows over the condenser.

The IAQ improvement device has the following advantages:

- Adding the UVGI to a used dehumidifier modifies an existing device by adding air purification parts at a low cost.
- This device is useful for biological and environmental researchers for terminating fungi and bacteria.
- The method given for constructing the modification and its electrical wiring will enable other researchers to follow the same method at a low cost compared to what is available in the market.
- This modified low cost dehumidifier will also be advantageous for people with low income as it consumes less energy.
- This proposed device is compact and easy to move from one living space to another, benefiting people living in overcrowded dwellings.

Design files

In this study, we are converting a second-hand dehumidifier by adding UVGI lights with the following specifications: L (300 mm), D (16 mm), power output (8 Watts), UV-C radiation output (253.7 nm) and 9000 h lifetime.

This modification requires changing the physical shape of the existing dehumidifier manufactured by General Electric Company Limited (GEC Ltd.) Model (DB48WH-NZGC), power output (240 Watts), compressor model (Tecumseh AZ0374YS), which uses R-134a refrigerant which is acceptable to operate in New Zealand as long as we do not interfere with the compressor. This dehumidifier provides a 0.018 m^3/s air flow rate and reserves five litres of condensed water using automatic shut-off when the reservoir is full; a warning light indicates that condition.

All components were reused excluding the outer case and the base as shown in Table 2. The reused components include the main tower, fan, evaporator, condenser, compressor, power switch, warning light, water reservoir, power cord and wheels.

Table 2
Design Files Summary.

Design file name	File type	Open source license	Location of the file
Divider	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Ballasts	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Base	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Compressor	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Condenser	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Evaporator	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Fan Motor	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Inner Frame	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Front Face	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Lamp Reflector	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Outer Case	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Tower	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
UV Tube	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Reservoir	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Water Tray	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Wheel	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Wire Guard	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2
Final Assembly	SolidWorks	TAPR OHL	https://doi.org/10.17632/bshhwy3czd.2

Table 2 shows the components needed to rebuild the modified dehumidifier. Also, details of the final assembly are given.

- Final Assembly – CAD file showing the assembled dehumidifier. This assembly file is supplementary to the design which could be used in further study such as computational fluid dynamics modelling.

Bill of materials

The Bill of materials in Table 3 shows the list, including the main components and collections of the smaller components excluding the dehumidifier.

Build instructions

A dehumidifier that was surplus (as shown in Fig. 1) was available to dismantle and repurpose for the project. The outer casing was removed revealing the inner workings and components to allow design of the product. It was decided to retain the dehumidifier's setup and extend the front section to allow the UV lights to be added.

To extend the front of the dehumidifier, the base plate was extended. This was done using a sheet of 2 mm galvanised mild steel with 20 mm edges folded upwards, with rear edge of 28 mm folded at 45° to aid in removal of the water container as shown in Fig. 2. This structure provided rigidity and mounting points for the walls and frame. The base was built using an angle grinder with a cutting disc to remove 20 mm squares from each corner (28 mm for rear edge). The fold lines were then

Table 3
Bill of materials

Designator	Component	Number	Cost per unit - currency	Total cost - currency	Source of materials	Material type
Used Dehumidifier	DB48WH-NZGC	1			General Electric Company Limited (GEC Ltd.) was not needed at home was available to dismantle and repurpose for the project	Off-the-shelf component
UV Light	Philips UV-C tubes	2	$30.95	$61.90	https://www.brcnz.co.nz	Off-the-shelf component
Ballasts	Tridonic electronic ballasts (4–13 W)	2	$22.00	$44.00	https://www.tridonic.com/	Off-the-shelf component
Light Switch	Light Switch with LED	1	$8.60	$8.60	https://www.showtechnix.co.nz/	Off-the-shelf component
Tube battens	T5 fluorescent tube battens	4	$3.00	$12.00	https://www.bunnings.co.nz/	Off-the-shelf component
Paint	White Paint	1	$18.00	$18.00	https://www.bunnings.co.nz/	Pigments, solvents, resins
Dehumidifier New Base	Sheet of 2 mm galvanised mild steel with 20 mm edges folded upwards				Donated	Galvanised mild steel
Four lengths of 19 mm by 19 mm	Aluminium square section tube	4			Donated	Aluminium
1 length of 20 mm by 20 mm c-channel	Aluminum extrusion	1			Donated	Aluminum
1.2 mm aluminum sheet	1.2 m by 900 mm	1	$20 (damaged)	$20	Mainline Sheetmetal	Aluminium
Partition (320 mm high and 360 mm wide) was cut and folded from a 1.2 mm Aluminium sheet	Aluminium sheet				Donated	Aluminium
M6 rivet nuts		16	$0.58	$9.28	Bunnings warehouse	Steel
10 mm screws		8	$0.085	$0.68	Nz.rs-online.com	Steel
Intake grill	Steel shower caddy	1	$15	$15	Bunnings Warehouse	Steel
M6 × 15 screws		16	$0.12	$1.92	Aimsindustrial.com	Steel
M6 spring washers		16	$0.03	$0.48	Nzsafetyblackwoods	Steel
M6 flat washers		16	$0.06	$0.96	NZsafetyblackwoods	Steel
4.8 mm rivets		38	$0.13	$4.94	Donated	Steel
Dual 10 30/30 24x12x2	Filter	1	$16	$16	Camfil Clean Air Solutions | Camfil	Blended Polyester

Total cost: USD $150.70 (≈ NZD $213.76).

Fig. 1. Dehumidifier components.

scored using the cutting disc (approximately 1 mm deep) to make folding easier and tidier. Folding was done by overhanging the edge off a solid bench and gently tapping into place with a hammer.

All components were removed from the original base plate and transferred to the extended one as shown in Fig. 3(a). The main tower was attached using 5 mm pop rivets. The unit's power cord passes through the base through a hole with flat sides to hold it in place. Rather than cutting this shape, a larger square was cut using an angle grinder with cutting disc and the hole from the original base was removed and reused with 4 rivets (Fig. 3(b)). The original wheels were reused by drilling M8 holes in all four corners, with care taken not to interfere with the new frame positioning.

Four lengths of 19 mm × 19 mm aluminium square section tube were used as the internal frame of the product. These were cut to length using a grinder with a cutting disc, then welded together using a MIG welder with aluminium wire and argon gas. The ends to be welded were cut at a 45° angle and the paint removed using a grinder with a sanding disc. The frame was then assembled with one length vertically on each corner (length 485 mm) then around the top edges to form a rectangular roof support (with lengths of 572 mm and 321 mm) as shown in Fig. 4.

The areas of the frame that were stripped of paint were repainted black and the frame was fitted to the dehumidifier using rivets as shown in Fig. 5. M6 rivet nuts were added to the sides of the frame at the base as well as the four corners on the front, allowing the case to be easily fitted and removed once built.

Four T5 fluorescent light batten holders were purchased from Ideal Electrical for $3 each. These were fastened with screws facing two aluminium sheets measuring 315 mm × 120 mm, folded into thirds with 45° folds (shown below). These act as reflectors to direct the light towards the moving air, with the lights being mounted at the top and bottom of the chamber. For the batten holders on the base, aluminium plates (Fig. 6 (d)) were fixed underneath with rivets, as the steel base was too hard for screws to thread into. The top light battens and reflectors were fixed to a piece of thin steel sheeting (Fig. 6 (c)) which was then fixed to the bottom of the top frame lengths with four M6 button head bolts and rivet nuts (these could also be substituted with pop rivets). The spacing between the two battens on each sheet was measured with the tube fitted and given a 2 mm gap at either side of the tube. The light fittings were fixed to the device with rivets, one on the base and one at the top of the frame as shown in Fig. 6.

An 18 W electronic ballast from a fluorescent light fitting was fixed to the base of the device (shown in Fig. 6) with two nuts and bolts. This was attached to the light battens with twin core wire.

Fig. 2. (a) New base folded and (b) Score lines before folding.

(a) (b)

Fig. 3. (a) Dehumidifier components on new base and (b) reused power cable hole.

Fig. 4. Frame once welded.

Fig. 5. Frame once painted and mounted.

Two UVC fluorescent T5 light tubes were purchased (from lightbulbshop.co.nz) for $30.95 each. These are 8 W, 300 mm germicidal tubes designed for sterilisation and disinfection. These screw directly into the fittings.

The UV lights, single electronic ballast and light switch were all connected to the 240 V power supply according to the wiring diagram in Fig. 7 (a). When power was applied it was found that one tube would only flicker or faintly glow at both ends while the other turned on. This was due to the ballast used being designed for only one fluorescent tube. Electronic

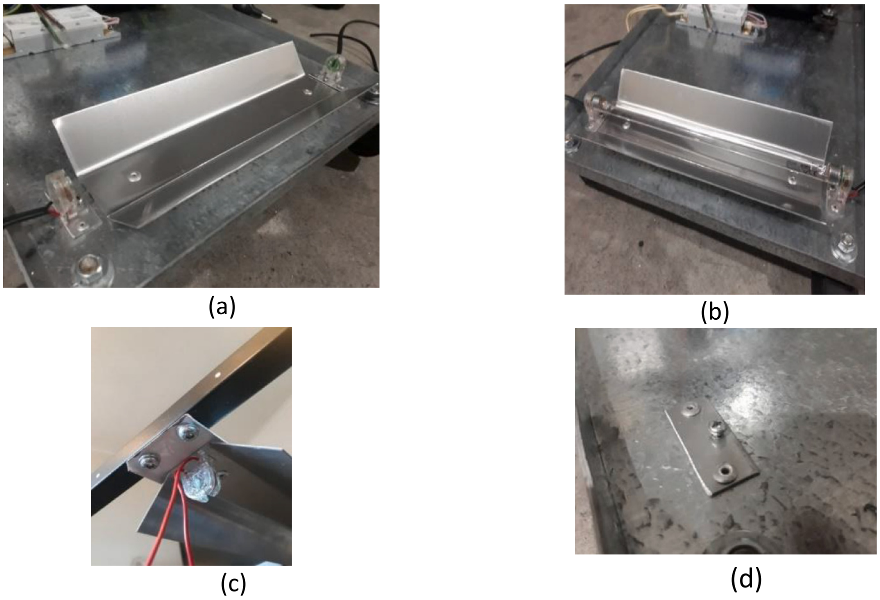

Fig. 6. (a) UVGI light fitting View 1 and (b) view 2, (c) top light fitting and (d) lower batten holder mounting point.

ballasts work by providing a high voltage to start the tube, then greatly dropping this voltage to maintain the power. Once the ballast detects that one tube has started, the voltage is dropped to the point where the second will not start.

To address this, two T5 electronic ballasts (4–13 W) were purchased to replace the single ballast as shown in Fig. 7 (b). These were installed on an elevated platform to protect them from water in the unlikely event of a spill from the water reservoir.

A partition (320 mm high and 360 mm wide) was cut and folded from a 1.2 mm aluminium sheet to direct air flow downwards past the lower UV lamp, increasing air exposure to the light. The partition was made from a 320 mm by 760 mm sheet, which then had two 200 mm by 300 mm rectangles cut off each side. This left the wall with two wings 200 mm by 60 mm on each side. These wings were then folded using the edge of a solid bench, then two 20 mm tabs were folded at the ends to provide mounting points. A vertical cut 20 mm long and 20 mm from the outside edge was then added to the two top corners using a cutting disc, allowing two tabs to be folded down for mounting to the top frame. The partition was then mounted to the top and front internal frame structure with pop rivets as shown in Fig. 8.

The front wall of the unit was cut and folded from 1.2 mm aluminium sheet. The top and sides had 10 mm edges folded back 90° to provide structural rigidity and strength. The fold lines for the outer edges were scored using a Stanley knife several times to aid in bending and to create a better fold. They were then folded using the edge of a solid bench and a hammer, gently tapping to minimise dents. A rectangular hole was cut for the intake (304 mm wide and 90 mm high, being sure to leave room for the frame) using an angle grinder with cutting disc, then smoothed with sandpaper as this edge will be visible.

A square for the light switch was made by marking an approximate size and then drilling as much material out as possible. The power knob for the dehumidifier was cut from the plastic face of the original unit using an angle grinder, being sure to retain enough material around the knob for adhesive. A hole in the new face was cut next to the light switch using

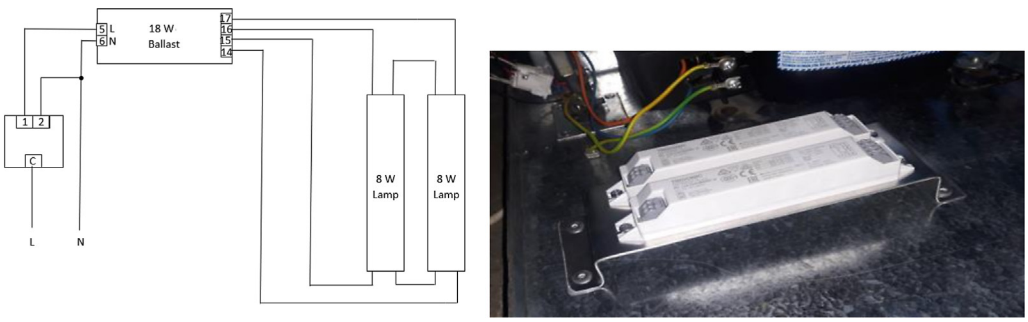

Fig. 7. (a) UV light wiring diagram for single ballast and (b) Two electronic ballasts mounted.

Fig. 8. Partition folded and ready to be attached.

a hole saw, approximately 15 mm smaller in diameter than the dial. This was then glued behind the hole using a 2-part epoxy resin.

The dehumidifier power and water indicator lights were attached using the same method as the power knob, by cutting a square in the new face and using epoxy to glue them in place after removing from the original face.

The intake grill was made using a steel mesh shower caddy found at Bunnings Warehouse for $15. This was cut to size (340 mm wide and 95 mm high) then fixed to the inside of the face using 2-part epoxy resin. Two strips of the same mesh (20 mm wide and 120 mm high) were cut to hold the filter in place once installed.

Two C-channel aluminium strips were attached to the inside of the intake with pre-attached double-sided tape. A polyester Dual 10 30/30 NZD $16 filter was cut to size and inserted into the C-channels as shown in Fig. 9 (b). This allows the filter to be replaced (when necessary) with any filter material of a suitable thickness that is cut to size. The Dual 10 30/30 filter is

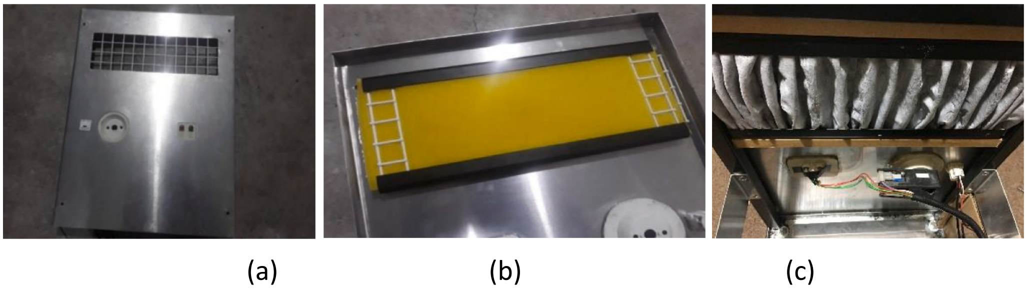

Fig. 9. (a) Front face completed, (b) two white filter clips and (c) the dual 30/30 filter.

Fig. 10. Interior of device completed.

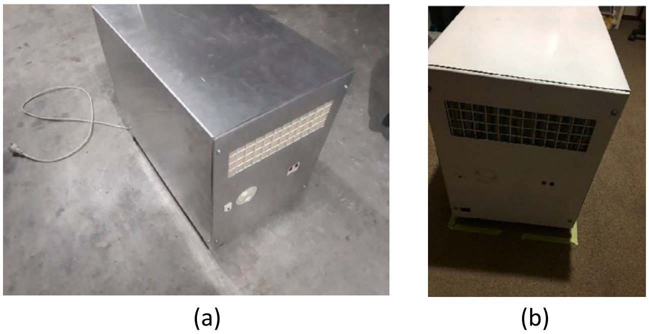

Fig. 11. (a) Exterior of device completed; (b) exterior of device painted white.

an ASHRAE MERV 8 class, air flow 1700 m^3/h, initial pressure is 70 Pa, maximum temperature 70 °C and relative humidity % is operational from 0 to 100.

The front face of the outer case was fixed to the front of the frame with four M6 button head bolts with M6 rivet nuts inserted into the frame. Once fixed, the wiring for the controls and power/full reservoir lights was connected as shown in Fig. 10.

The outer case was cut from a flat sheet of 1.2 mm aluminium into a rectangle measuring 620 mm by 1346 mm. This was then taken to McLeod's Sheetmetal who folded it with two 90° folds. This was attached to the unit with M6 rivet nuts and M6 button head screws, two either side at the base of the frame. Gaps were visible between the case and the front face (Fig. 11 (a)) so four more screws were added either side.

The unit was painted white to make it more attractive and less industrial looking as shown in Fig. 11 (b). Several layers of clear coat were then applied to further enhance the appearance and make the paint more durable.

Operation instructions

Place the IAQ improvement device in the room that requires moisture, fungi, and bacteria removal, being sure not to block any air vents. Then plug in and start the dehumidifier and after few seconds, switch the UVGI light on.

Replacing UV lights

The UV lights have a rated average lifetime of around 9000 h (or 375 days). In other words, on average, they will run for two years if used for 12 h a day. However, most households will not require that usage as humidity and low temperature are much less of an issue in the summer. If a tube does fail, however, it can easily be accessed and replaced by:

- Turn the device off and unplug the power cord.
- Unscrew the 12 M6 button head bolts on the sides of the unit with an H4 hex bit (or Allen key).
- Lift the outer case up and off the frame. The tubes can then be easily accessed.
- Remove the tubes by rotating them 90° and sliding them out of the batten holders and dispose of them safely.
- Slide the new tubes into the batten holders and rotate 90° to lock them in place.
- Replace the outer case and screw the 12 bolts back in (do not over-tighten).

Filter replacement

The Dual 10 30/30 filter measures 320 mm by 120 mm. The old filter can be removed by removing the outer case as outlined in Fig. 9. Once accessible, the two white filter clips can be removed by rotating them until they can be removed from the channels. The filter can then be removed and replaced with a new filter and the clips replaced.

Validation and characterisation

Mould growth and spread require a suitable environment, consisting of sufficient humidity (RH of 50% or above), a temperature between 0 and 50 °C, and dust as an organic material which provides a food source for mould. To eliminate and reduce mould growth we should achieve 30–50% relative humidity and remove the dust in indoor dwellings.

The proposed devise was placed in a residential house located in Waikato, New Zealand. The primary method of testing was by comparing our design with a commercial device (City Touch, cost NZD $1350 + GST) using an air image sensor (#01325) placed in the room as shown in Fig. 12 (a) for current device and Fig. 12 (b) for City touch device. The City Touch fan operates with five speeds. For the purpose of this study we set the City touch to the lowest speed setting (1.5 m/s) which is the closest to the dehumidifier's operating speed of (1.45 m/s) measured by a vane anemometer (Testo 410–2) sensor, which a plastic impeller sensor with an accuracy of ±(0.2 m/s + 2% of the reading).

The air image sensor (#01325) was placed at a height of 0.8 m in the room, and a distance of 1.1 m from the front face of the dehumidifier, as shown in Fig. 12. Data were captured across a 72 h-period, from 20:30 on the 17th of August 2021 till 20:30 on the 20th of August 2021. The air image sensor is manufactured by Camfil AB, (Stockholm, Sweden) and operates using the internet of things (IoT) method in monitoring the indoor air quality (IAQ) using Realtime data validated against the WHO levels. This sensor measures temperature (T °C, from −10 to + 50 with an accuracy of ±3), relative humidity (% RH, with an operating range of 0–100 no condensation), particulate matters (PM_1, $PM_{2.5}$ and PM_{10}) $\mu g/m^3$ and requires a 5 V DC power supply. To access the data we used the Camfil sensor login Realtime monitoring dashboard as shown in Fig. 13. The experimental validation was designed as shown in Table 4(a) for the modified dehumidifier and Table 4(b) for the City Touch device. Table 4(a) shows the setup and measured data at the time we ran the dehumidifier without the UV light and with the UV light, and provides a comparison for indoor and outdoor environmental parameters such as temperature, relative humidity and particulate matters ($PM_{2.5}$).

On the 18th of August, we tested our device for two hours without the UV light, from 14:00–16:00, and then the device was run with the UV light, from 16:00–18:00. We then repeated the procedure from 22:00 – 23:59 without UV lights and from 00:00 till 6:30 with UV lights. This process was run the following day, on the 19th of August, for the City Touch device, as shown Table 4(b).

The sensor #01325 monitored the results for the 72 h period, as shown in Fig. 13. This figure shows that, the modified dehumidifier achieved an acceptable range of RH of below 50%, compared to the City Touch where the RH was higher than 55%. As mentioned earlier, lowering RH is an important component in limiting favourable conditions for mould growth. The modified dehumidifier also achieved overall higher temperatures during operation with UVGI light, as shown in Fig. 13 (pe-

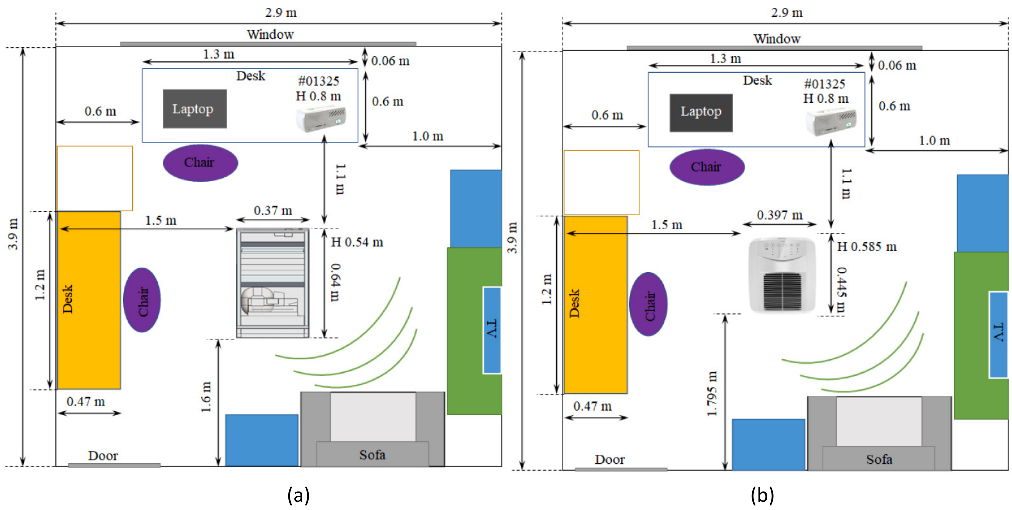

Fig. 12. The schematic diagram (a) for the dehumidifier and (b) city touch, showing the air image sensor location used in this study.

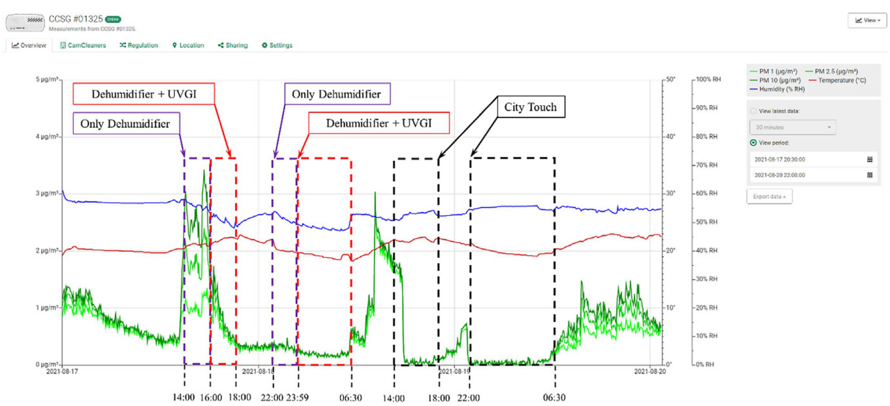

Fig. 13. Camfil dashboard for monitoring the IAQ data for both devices showing the 72 h period.

Table 4(a)
Testing schedule for the modified dehumidifier.

DATE	TIME	ACTION	TEMPERATURE(T °C)			Relative Humidity (%RH)		Particulate Matter ($PM_{2.5}$ -$\mu g/m^3$)	
			Indoor	Outdoor	ΔT^*	indoor	outdoor	indoor	outdoor
17/08/2021	20:30	Air image sensor (#01325) switched on	19	9	10	62	72	0.9	2.76
18/08/2021	14:00	Dehumidifier on (no UV light) Petri dishes taken	21	9	12	56	74	1.8	5.76
18/08/2021	16:00	UV light is switched on	22	9	13	51	84	0.65	5.76
18/08/2021	18:00	Dehumidifier + UV light off	22	9	13	49	84	0.4	5.76
18/08/2021	20:00	Off	22	7	15	53	90	0.3	2.77
18/08/2021	22:00	Dehumidifier switched on	22	6	16	53	90	0.34	2.77
18/08/2021	23:59	UV light switched on Petri dishes taken	20	5	15	51	90	0.52	2.77
19/08/2021	00:00	UV light switched on	20	3	17	51	90	0.52	2.77
19/08/2021	06:30	UV light switched on	18.5	3	15.5	47.14	90	0.14	2.77

$\Delta T^* = T_{Indoor} - T_{outdoor}$ for the modified dehumidifier

Table 4(b)
Testing schedule for the City Touch device

DATE	TIME	ACTION	TEMPERATURE (T°C)			Relative Humidity (% RH)		Particulate Matter ($PM_{2.5}$ -$\mu g/m^3$)	
			Indoor	Outdoor	ΔT^{**}	indoor	outdoor	indoor	outdoor
19/08/2021	14:00	City Touch switched on Petri dishes taken	21.8	14	7.8	53	58	1.5	7.07
19/08/2021	16:00	City Touch on	22.2	11	11.2	53	79	0.05	7.91
19/08/2021	18:00	City Touch off	22.2	9	13.2	55	79	0.25	7.91
19/08/2021	20:00	Off	21.9	9	12.9	53	65	0.35	6.9
19/08/2021	22:00	City Touch switched on	21.1	9	12.1	53.57	67	0.725	5.2
19/08/2021	23:59	City Touch on Petri dishes taken	20.4	6	14.4	55.3	68	0.05	4.2
20/08/2021	00:00	City Touch on	20.4	6	14.4	55.3	70	0.05	5.3
20/08/2021	06:30	City Touch on	19.10	6	13.1	55.9	70	0.05	5.3

$\Delta T^{**} = T_{Indoor} - T_{outdoor}$ for the City Touch

riod 16:00 – 18:00) compared to the City Touch, however this outcome matters more for thermal comfort of humans, as the temperature is still in the favourable range for mould growth. In terms of particulate matters, the City Touch achieved better results, with a value of 0.05 $\mu g/m^3$ (a reduction from 1.5 $\mu g/m^3$) however, our device did achieve a reduction in particulate matters, from 0.9 $\mu g/m^3$ to 0.14 $\mu g/m^3$, which reduces the favourable conditions for mould growth. The main reason that the City Touch performed so well in relation to particulate matters' reduction was that it uses three different types of filters; a Nylon PRE filter to remove large dust, a GigaPleat performance Molecular filter to remove indoor odours, second hand smoke and volatile organic compounds (VOC) and then a fine HEPA H13 filter to remove small diameter particulates, including dust mites and pollen. These filters come with a higher cost, as mentioned earlier: NZD $1350 compared to our device's NZD 213.76. Our device is specifically designed to suit people on lower incomes.

Microbial pollution is a form of indoor air pollution caused by bacteria and fungi. These microbes thrive in indoor environments due to their favourable temperature and high relative humidity. We investigated the effect of exposing these microbial populations to UVGI lights. Petri dishes containing commercially prepared Potato dextrose nutrient agar were used as the growth medium for the samples. Cotton bud swabs were taken from indoor wall surfaces where there was observable dampness and mould, and these were transferred to the surface of the agar plates, then left to incubate at 24 °C for 5 days to allow colony formation. Fig. 14 shows the petri dishes taken during the testing. Fig. 14 (a) and (b) show the fungi growth in the room before using any device or HVAC. Fig. 14 (c) and (d) show a reduction in fungi growth after operating the dehumidifier and UVGI lights at (23:59). Fig. 14 (e) and (f) show how the city touch device impact on the mould growth. It should be noted that the UVGI light clearly impacts on the fungi growth; furthermore, since the City Touch was used the following day, it is possible that this effect carried over, and impacted on the performance of the City Touch. For future study we will investigate each device for a longitudinal study in an identical room.

Fig. 15 shows the $PM_{2.5}$, Temperature and Relative Humidity readings for both devices running from 22:00 till 6:30 to validate the outcome of our low-cost device. Also, it is important to note that the outdoor conditions were colder for the date when we ran the modified dehumidifier compared to the date when we ran the City Touch, as shown in the outdoor conditions columns for Tables 4(a) and (b). Our design achieves a big improvement with respect to relative humidity and temperature. For example, the average temperature value for the modified dehumidifier for $\Delta T = T_{indoor} - T_{outdoor} = 16.61°C$ whereas for the City Touch this temperature difference is 13.91 °C. Neither device have a purpose-built heating element.

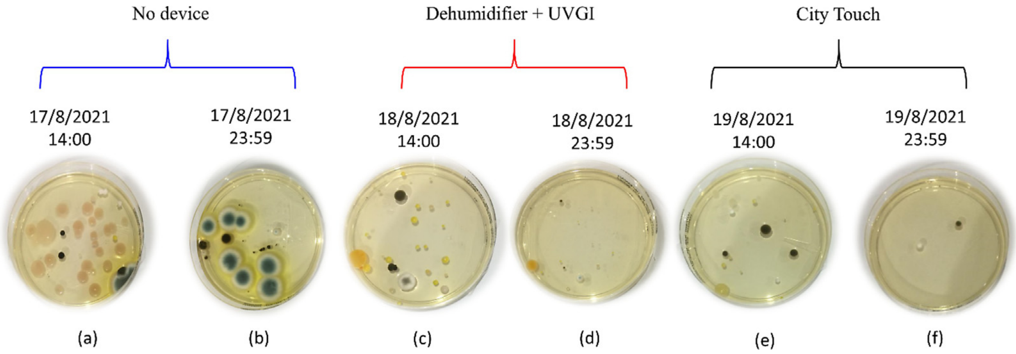

Fig. 14. The petri dishes used to identify fungi growth with (a) no device at 14:00 (b) no device at 23:59, (c) before operating the dehumidifier + UVGI, (d) during the operation of the dehumidifier + UVGI light, (e) before operating the City touch device, (f) during the operation of the City touch device.

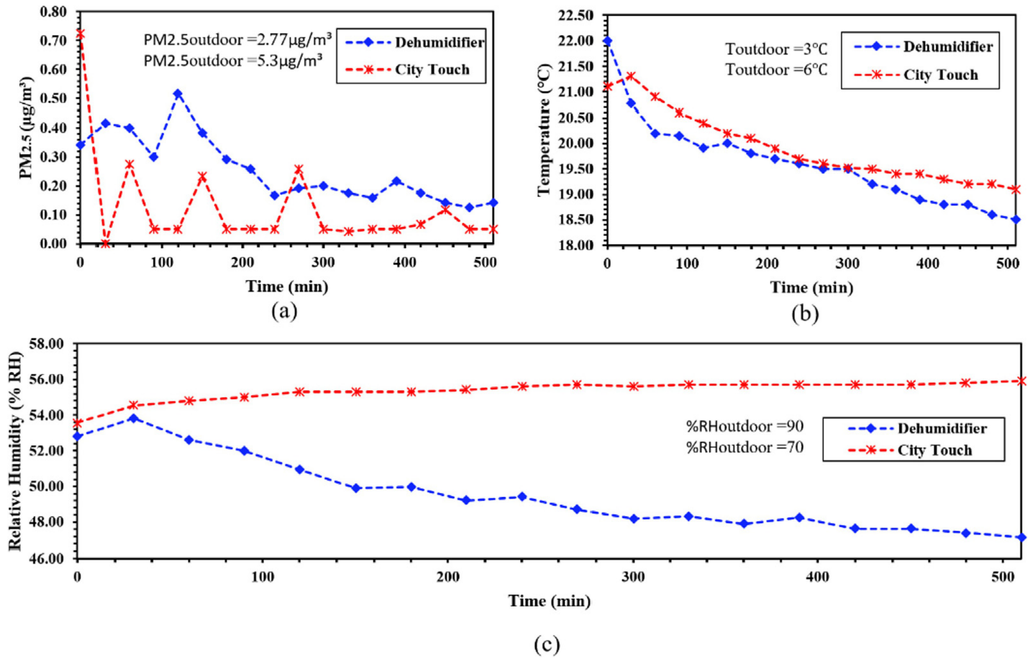

Fig. 15. (a) The Particulate matter PM2.5, (b) Temperature, and (c) the Relative humidity; for both devices running from 22:00 till 6:30.

With respect to relative humidity, our modified device achieves a significant reduction in indoor RH, with a difference of 14% (whilst outdoor RH was between 72 and 90%). The City Touch did not impact on RH as that is not part of the functionality of the device.

In conclusion, to reduce the conditions favourable to mould growth, we have described how a low-cost device can be constructed, consisting of a dehumidifier modified to include UVGI lighting and filtration. This modified device performed extremely well at reducing the relative humidity in the room and relatively well at reducing particulate matters in the room. Those two elements were important to eliminating the conditions suitable for mould growth. The modified device had the additional benefit of raising the temperature, which impacts thermal comfort of the human occupants in the room, though this does not impact on mould growth. Such a modification was achieved relatively easily, at low cost, as described in section 5, which suits the objective of providing a device suitable for lower income households. Additionally, the dehumidifier uses 170 Watts for the device itself (without UVGI lights) and then additional 18.5 Watts for both UVGI lights switched on which amounts to an operating cost of around NZD $87.6 per year; however, the City Touch consumes $43.8 per year (using 43 Watts). The lower cost of the latter is due to the fact that it does not perform dehumidification. The cost of the dehumidifier could be improved by a more modern dehumidifier. In addition, our next project aims to run the device using solar energy to defray the cost for low-income users.

Human and animal rights

No human or animal studies were conducted in this work.

CRediT authorship contribution statement

Mohammad Al-Rawi: Conceptualization, Methodology, Writing – review & editing. **Annette Lazonby:** Data curation, Writing – original draft. **Callan Smith:** Construction, Prototyping & Testing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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