Energy Reports 13 (2025) 2545–2554

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Integrating smart air purifiers in building controls: A conceptual approach to infection and energy management

Onur Kocak [a], Ulviye Bunyatova [b,*]

[a] Baskent University, Computer Engineering Department, Engineering Facility, Ankara 06790, Turkiye
[b] Baskent University, Biomedical Engineering Department, Engineering Facility, Ankara 06790, Turkiye

ARTICLE INFO

Keywords:
Smart Adaptive Air Control System
Motion &Dust Sensors
Photocatalytic Nanocoating
Energy management
S Antiviral efficiency & SARS-Cov-2

ABSTRACT

The COVID-19 pandemic has highlighted the critical need to maintain high indoor air quality. While in-duct systems are effective, their high installation costs make portable systems a more accessible and cost-effective alternative for improving indoor environments. However, energy consumption remains a key challenge with existing solutions. This study introduces the Adaptive Air Purification and Ventilation System (APVS), an intelligent technology designed to improve air quality, control airborne infections, and optimize energy use in residential and public spaces. The APVS integrates adaptive fan control with IT applications, motion sensors, and dust and virus particle sensors. Using real-time data, it dynamically adjusts ventilation based on occupancy, providing energy-efficient and effective antiviral protection. A case study was conducted in a public administration building with 14 employees and a total indoor volume of 1170 m^3 to be cleaned. The performance of the APVS was also compared to three commercially available units. Key results demonstrated the superiority of the APVS in key metrics: an air turnover rate of 4.49 units/h versus 2.61 units/h, energy efficiency per unit volume of 0.001388 kW/m^3 versus 0.001412 kW/m^3 , and effective air cleaning capacity of 1750 m^3/h versus 1510 m^3/h. In addition, its adaptive sensing technology reduced power consumption to 1.7 kW, demonstrating significant energy savings. These results establish the APVS as a sustainable, innovative solution for improving indoor air quality, reducing airborne infections, and saving energy, making it highly suitable for various applications.

1. Introduction

The COVID-19 pandemic highlighted a critical oversight in building environments: the neglect of indoor air quality and its resilience. Since SARS-CoV-2 and other viruses are primarily transmitted through respiratory aerosols, it is essential to understand how building HVAC systems and their resilience affect the risk of airborne transmission indoors (Lepore et al., 2021; Yue et al., 2006; Benito et al., 2021; Carlos et al., 2020; Staszowska, 2020; Morawska et al., 2020; Bian et al., 2024).A key strategy to mitigate airborne transmission is to improve ventilation and air conditioning systems while effectively managing indoor population densities (Moghadam et al., 2023).

Conventional air treatment and purification systems often rely on multiple energy-intensive equipment and air handling systems (Staszowska, 2020). The use of air filters, such as High Efficiency Particulate Air (HEPA) filters, is widespreads residential and industrial environments (Kim et al., 2023; Bakhtiari et al., 2014); these filters remove particulate pollutants from the air, ensuring a cleaner and healthier indoor environment for occupants. In light of the above literature review, it's clear that rapid technological advances are enabling the construction of energy-efficient buildings with integrated HVAC systems. However, a crucial aspect to consider is the potential risk posed by viruses such as COVID and volatile organic compounds (VOCs) to the human respiratory system (Risbeck et al., 2022). Consequently, there is an urgent need to develop innovative technologies that can create a hygienic and comfortable indoor environment while optimizing buildings. On the one hand, we have identified several innovative solutions, such as the improvement of HEPA filters with photocatalytic processes (Lindblad et al., 2020) and the integration of UV-C light in cleaning systems (Narla et al., 2020).

From one point of view it is crucial to innovate and develop novel technologies with energy management systems that support resilient air purification and create hygienic and comfortable indoor environments with smart control systems (Nair et al., 2020). A literature review of the last two decades shows that studies on energy conservation in HVAC systems have become increasingly important, establishing it as one of the most prominent topics worldwide (Vakiloroaya et al., 2014; Belussi

---

* Corresponding author.
E-mail addresses: onurkocak@gmail.com, okocak@baskent.edu.tr (O. Kocak), bunyatovau@yahoo.com, ubunyatova@baskent.edu.tr (U. Bunyatova).

https://doi.org/10.1016/j.egyr.2025.01.072
Received 27 November 2024; Received in revised form 21 January 2025; Accepted 27 January 2025

Nomenclature

APVS	Adaptive Air Purification and Ventilation System
HVAC	Heating, Ventilation, and Air Conditioning
IT	Information Technology
CO	Carbon monoxide
CO_2	Carbon dioxide
HEPA	High Efficiency Particulate Air
UV	Ultraviolet
LDR	Light Dependent Resistance
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
EC FAN	Electronically Commutated
UV-LED	Ultraviolet Light Emitting Diode
AC	Alternative Current
UV-C	Ultraviolet Light C -band
RNA	Ribonucleic acid
DNA	Deoxyribonucleic acid
Air Cycling Rate	The air cycling rate = (units of air cycled per hour) was calculated using the formula: Air Cycling Rate=Effective Volume/Total Time (hours)
Energy Efficiency per Unit Volume	Energy consumption per unit volume of air purified was determined using: Energy Consumption per Volume=Total Energy Consumption/Effective Volume
Effective Volume	The effective volume was based on each device's air purification capacity per hour, derived from manufacturer specifications and verified during testing.
Energy Savings via Adaptive Technology	Energy savings were calculated based on the power reduction enabled by motion and dust sensor feedback, leading to adaptive fan speed control. The adjusted energy consumption for APVS was calculated as: Adjusted Energy Consumption =Total Energy Consumption−Energy Saved
Lower Adjusted Energy Consumption per Volume	The adjusted energy consumption per volume was calculated using: Adjusted Energy Consumption per Volume= Adjusted Energy consumption /Effective Volume

et al., 2019). These sources were not merely technical alternatives, but represented a profound shift in energy production and consumption, reflecting a broader commitment to sustainability, resilience, and a more harmonious relationship with nature. Broujeny and co-authors propose an advanced heating control strategy that exploits the presence of occupants as additional heat sources by modeling heating dynamics using a multilayer perceptron neural network for time-series prediction. This adaptive controller, implemented in a five-story building at the Senart Campus, integrates a fuzzy inference system based on the Takagi Sugeno model to optimize heating management while considering occupant behavior (Broujeny et al., 2021). Dgrona and colleagues, in their review of HVAC systems, provide a comprehensive categorization of key modeling approaches, co-simulation methods, optimal control strategies, and optimization tools and solvers designed to address MPC challenges in the field of building climate management (Drgoňa et al., 2020). X. Cui and co-authors investigated a hybrid air treatment system for tropical climates that combines an ozone-based oxidation process with air scrubbing, and experimentally demonstrated its effectiveness in improving indoor air quality. The energy efficiency of the system was evaluated using a validated mathematical model, demonstrating reduced cooling loads and improved chiller performance in office buildings (Cui et al., 2017). Vogth's publication uses the Cyber-Physical Production System (CPPS) framework to compare the performance of four main control schemes, ranging from simple time-based control to model predictive control, in the context of battery production, a first in the field. Using a case study at the Battery LabFactory Braunschweig (BLB), this analysis shows that all investigated control approaches significantly reduce the final energy demand, with model-predictive control achieving reductions of up to 37.29 % compared to the initial state. Yuexin Bian (Bian et al., 2024) proposed an innovative framework for learning and control in ventilation and thermal management to improve energy efficiency. This framework, validated through case studies of temperature and CO2 field modeling, outperforms traditional methods by reducing energy consumption, maintaining air quality and safety standards, and opening avenues for advances in airflow modeling and uncertainty integration for HVAC systems. Niu and co-authors developed an adaptive PM2.5 air filtration system that combines elastic TPU filters with IoT technology, enabling real-time adjustment of filtration performance based on air quality conditions. When applied to mechanical ventilation systems in different cities, the system achieved annual energy savings of up to 26.4 % in Hong Kong compared to traditional fixed systems, without compromising the effectiveness of pollution control. Schieweck et al (Schieweck et al., 2018). highlighted that the implementation of effective and cost-efficient engineering controls, such as adequate ventilation, particle filtration, and air disinfection, can significantly contribute to infection control goals. They emphasized that integrating these measures in public buildings, including hospitals and transportation facilities, along with other controls, could play a critical role in reducing transmission risks and protecting healthcare workers, patients, and the public worldwide.

Melikov et al. (2020) reported that ventilation is an effective engineering measure to mitigate airborne transmission, with increased outdoor air supply helping to dilute airborne aerosols. However, many existing mechanical ventilation systems, designed for energy efficiency under non-pandemic conditions, lack the capacity to sufficiently increase airflow during outbreaks. They proposed a control strategy that focuses on source control, suggesting intermittent pauses in room occupancy during which all occupants periodically leave and occupancy time is minimized. This strategy, tested in a typical classroom designed according to the European standard EN16798–1:2019 for 15 people with a floor area of 81 m^2, proved to be effective in reducing the risk of airborne transmission. Chen Ren (Ren et al., 2023) emphasized that in the post-COVID-19 era, simultaneously reducing infection risks and optimizing energy efficiency in public buildings is both essential and challenging. However, inefficient management of ventilation and cleaning systems can lead to higher energy consumption and increased risk of cross-contamination. Moghadam and colleagues conducted a comprehensive review of studies published between 2020 and 2022, focusing on four key research areas: the maturity of the existing literature, building types and occupancy patterns, ventilation methods and their control strategies, and challenges associated with these systems (Moghadam et al., 2023). Their analysis revealed that while HVAC auxiliaries are proving effective, the challenge of increasing fresh air supply remains due to its significant impact on the energy consumption required to maintain indoor air quality (IAQ). Based on their findings, the authors recommend exploring innovative approaches to reconcile the competing goals of reducing energy use while improving IAQ, evaluating ventilation control strategies in different building contexts, and promoting energy efficiency, resilience, and health in indoor environments.

Based on the above, it is clear that innovation and development of novel technologies to promote resilient air purification systems integrated with energy management solutions is critical. Such systems should ensure hygienic and comfortable indoor environments while employing cost-effective smart controls. This review also shows that the existing literature on heating, ventilation, and air conditioning (HVAC) systems focuses primarily on model-based energy efficiency improvements for office and residential buildings, with limited comparative analyses of the performance of control systems in improving energy efficiency.

Motivated by this gap, we present our study that introduces an innovative adaptive air purification device, APVS, designed for energy management and improved indoor resilience through smart motion sensors. Our concept proposes that resilient indoor air ventilation and purification can be automatically adjusted based on population density. In addition, to evaluate the efficiency of the APVS, we conducted a comparative analysis of its energy-efficient features with three globally recognized air ventilation devices. By actively circulating and purifying air within a specified building area of 390 m^2 and volume of 1170 m^3 , the APVS demonstrates its ability to provide a cleaner and healthier indoor environment.

2. Experimental part

2.1. Instrumental part - mechanical concept

The innovative solution for energy management and robust automation of air purification and ventilation involves the implementation of adaptive fan control. Fan control integrated with motion and dust sensors. In fact, the population of people in public places can change with the circulation of individuals, and we can track this change using dust and motion sensors. (Fig. 1).

These sensors can monitor over a wide time frame and integrate the signals received from the dust sensor. If no movement is detected in the vicinity for at least 30 min, the unit optimizes energy consumption by reducing to minimum level 1 operation. This adaptive fan continuously gathers information, enabling the air purifier to automatically increase the resilience of the indoor environment by increasing ventilation levels when population density reaches a critical threshold. Unlike traditional air purification systems that typically operate on preset schedules or require manual adjustments, our system integrates motion sensors to continuously monitor population changes in real time. This ensures that ventilation and air purification efforts are aligned with actual occupancy patterns rather than fixed schedules.

The advanced adaptive ventilation system (hereafter APVS) presented here also uses an activated carbon filter with titanium dioxide (TiO2) photocatalytic particles (hereafter AC@TiO2) combined with UV-C LEDs. (Fig. 2). The APVS uses a novel AC@TiO2 filter and a UV-C source with a wavelength of 263 nm (Fig. 2). In addition to filtering dust and synthetic materials, this device is designed to actively combat organic microorganisms and is optimized to kill and inactivate infectious biological agents. In general, UV-C emits high-energy photons in the 200–290 nm range and has significant potential for germicidal disinfection. The energy of these photons is sufficient to damage and degrade the nucleic acids (DNA/RNA) present in various microbes such

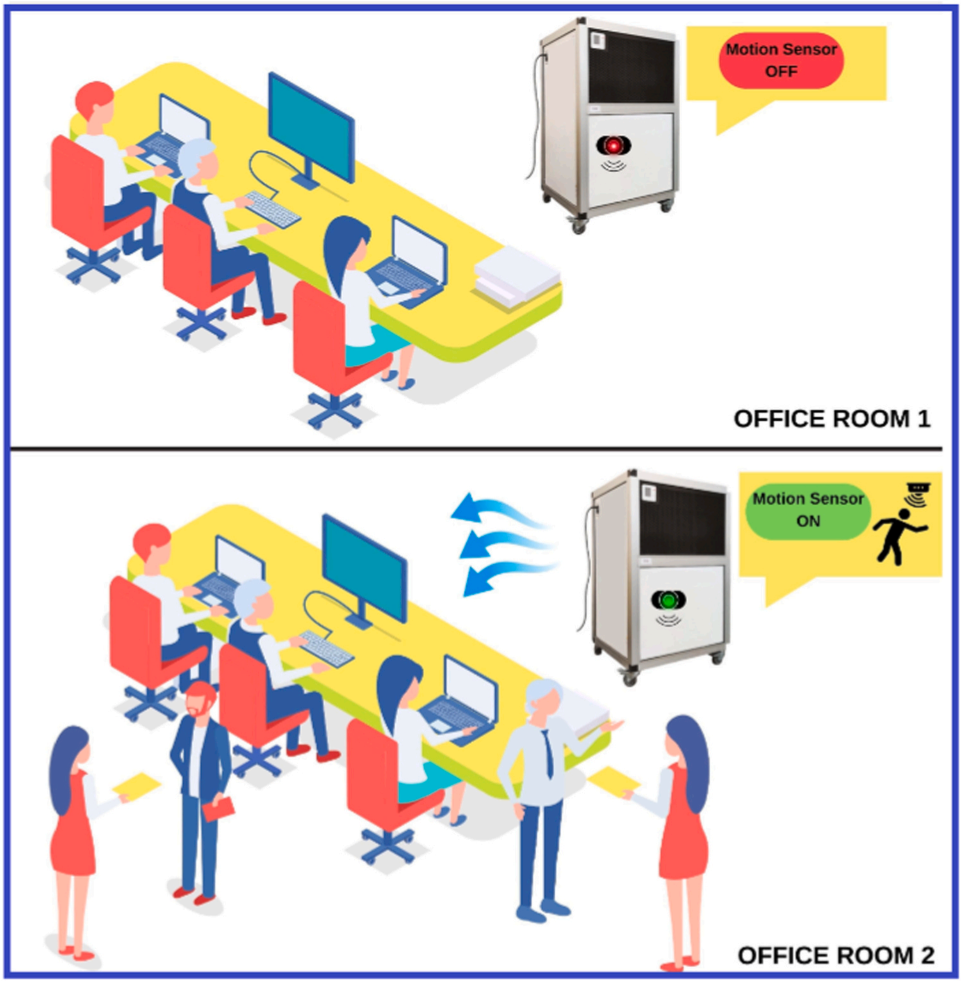


Fig. 1. APVS device: a schematic illustration of how adaptive fans work. The smart ventilation system features an adaptive fan control system integrated with a motion sensor and a dust sensor to manage energy consumption and automatically regulate indoor environmental conditions (office room 1). This adaptive fan continuously gathers information, enabling the air purifier to automatically improve the resilience of the indoor environment by increasing ventilation levels when the population density reaches a critical threshold. (Office Room 2). When the motion sensor detects movement in the room, it assumes that the environment is unstable, predicts that pollutant levels are high, and continues to operate at high speed. It also tries to optimize this situation by monitoring the dust sensor output. If a decrease in dust sensor output is detected approximately 5 min after maximum operation, the system reduces the operating level to improve energy efficiency.

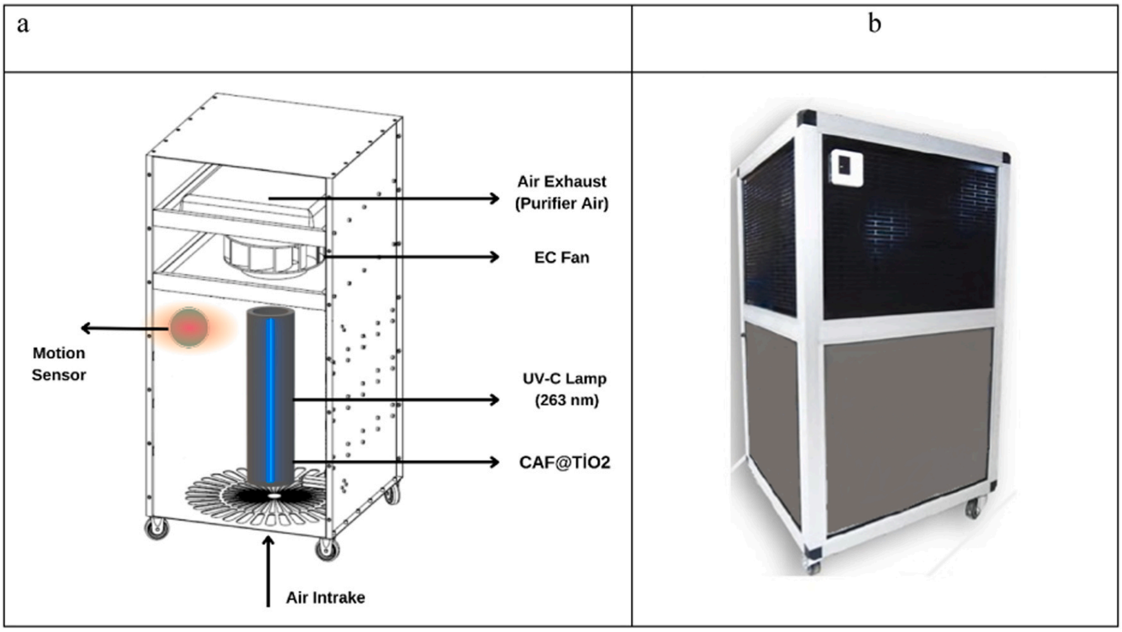


Fig. 2. Fig2a illustrates the mechanical concept of the APVS. The motion sensor, with a 180° field of view, is mounted on the panel of the APVS. The device has an innovative AC@TiO2 filter integrated with UV-C (263 nm) LEDs, along with a built-in fan. The real dimensions of the APVS are as follows: width: 780 mm; depth: 700 mm and height: 1230 mm. The image of the prototype APVS device is shown in Fig. 2b.

as bacteria, fungi and viruses.

Fig. 2 below illustrates the mechanical concept of the APVS (a), which is briefly described in Table 1. Fig. 2b shows a photograph of the real APVS machine.

The EC fan is controlled by the microcontroller via SSR, and this process is possible due to the controllable feature of the fan. (Fig. 3a). The control algorithm developed in this study is intentionally simple as it reflects both the controllable future of the fan itself and the preliminary nature of this research stage. This simplicity ensures compatibility with the current fan design while providing a basis for further development in subsequent studies.

2.2. Instrumental part - electrical and electronic and IoT application concept

The electronic block diagram of the APVS and the motion sensor flow chart are shown in Fig. 3a-b The microcontroller oversees various sensors and system components, including Light Dependent Resistance (LDR) to measure the light level of the environment Dust sensor to measure the amount of particles in the air Temperature sensor to monitor the room temperature of the EC FAN, which adjusts its speed based on the room temperature readings, controlled by a solid-state relay (SSR) (Fig. 3a). The SSR manages both AC power and fan speed. The data collected by these sensors is transmitted to the microcontroller, which analyzes it and performs necessary control and optimization operations to improve system performance. The system also incorporates photocatalytic activity and UV protection mechanisms, emitting radiation at a wavelength of 263 nm. A proprietary electronic driver operates the system components. This driver, powered directly from the 220 V AC grid, ensures smooth operation of the system. The motion sensor flow chart shows the operating principles of the adaptive fan. (Fig. 3b). The system's fan is designed to operate in three stages: slow, medium, and fast. Users can manually select the desired speed and duration. In addition, the system's closed-loop design provides adaptive speed control and improved energy efficiency. When set to adaptive mode, the system initially operates at medium speed (level 2) for 5–7 min. During this time, it uses a 180° motion sensor to monitor environmental motion. Monitoring and data collection takes between 15 and 20 s, depending on the design. This monitoring process repeats every 5 min. If the motion sensor detects motion more than half of the time during data collection, the system also checks the dust sensor.

The dust sensor measures the amount of dust entering the device and categorizes it into three levels:

- 0–20 ppm: The machine operates at low speed (Level 1).
- 21–39 ppm: The machine operates at medium speed (Level 2).
- Above 40 ppm: the device operates at high speed (level 3).

When the motion sensor detects limited motion for 10 min, the system checks for changes in the dust sensor. If there is no change, the machine operates at low speed. If no movement is detected for 10 min, the machine enters standby mode.

2.3. Modified air filtration and purification for air quality & airborne infection control

The concept of the adaptive APVS device with a motion sensor uses an activated carbon filter with titanium oxide photocatalytic particles (hereafter AC@TiO2) combined with UV-C LEDs. This activated carbon filter efficiently captures even the smallest particulate matter and airborne dust present in the air. In addition, this TiO2-incorporated filter, enhanced by a photocatalytic agent, also exhibits remarkable efficacy against microorganisms, including the SARS-CoV-2 model, under UV light illumination. The UV light acts as a photoactivator in conjunction with the TiO2 photocatalytic materials incorporated in the filter. This synergy exhibits virucidal and bactericidal effects by utilizing both the inherent ability of UV light to directly deactivate viral particles and bacteria by damaging nucleic acids and proteins, and the generation of oxidative radicals upon irradiation of the TiO2 surface (Bourezgui et al., 2016; Toro et al., 2020; Zhou et al., 2021). This process effectively eliminates fungi and combats diseases caused by airborne bacteria.

Table 1
Mechanical components of the APVS and description.

Mechanical Part	Description	Function
Energy-efficient Blauberg EC curved model fan:	Operated based on environmental occupancy, (power of 0.94 kw/(m3/s).	Air Quality & Airborne Infection & Energy Control: This adaptive fan continuously gathers information, enabling the air purifier to automatically improve the resilience of the indoor environment by increasing ventilation levels when population density reaches a critical threshold. Energy consumption is reduced by 30–35 %
Adaptive Fan Control	Integrated with motion sensor to control the dust sensor and enable to automatic control. Additionally, users can manually adjust engine	Air Quality & Airborne Infection & Energy Control: If no motion is detected in the area for at least 30 min, the unit optimizes power consumption by dropping to Level 1 operation..
Touch LCD Panel	Enabling users to view sensor data	Users can adjust engine speed
Light Sensor (LDR Sensor)	Monitors the lamp responsible for the photocatalytic effect in the system Linear operation between 200 and 1700 nm	When light levels fall below specified lumens, the sensor triggers an alert
SSR	6 channel low level triggered Isolation Voltage4 kV Input Current max 25 A Forward Current15 mA	Six relays facilitate engine and lamp control.
Temperature Sensor	Monitors temperature (between 0 and 120 °C); Humidity data.(operation conditions between −40 to +100 °C; and 0–100 %RH)	Displaying information with high accuracy (humidity: 5 %, temperature: 1 %)
Dust Sensor	Measurement range 0–1000 μg/m^3 ; Accuracy ± 20 μg/m^3 or ± 20 % of reading(@voltage 5.0 V, 25 ± 2°C, 50 ± 10 % RH)	**Air quality & airborne infection control** Alerts users to any unwanted air leaks, ensuring system integrity.
TiO2 Photocatalytic Filter + UV-C Lamb	Enhanced TiO2-incorporated carbon-activated fiber	**Air quality & airborne infection control:** Motion detection using signals from the dust sensor works as follows: When the motion sensor detects movement in the room, it assumes that the environment is unstable and requires increased resilience. The motion sensor predicts that the level of contaminants is high and works at high speed. To optimize the situation, it monitors the output of the dust sensor. If a decrease in dust levels is detected approximately five minutes after maximum operation, the system reduces its operating level to improve energy efficiency.

3. Results and discussion

3.1. *Air filtration test*

he standard air cleaning test was conducted at the Turkish laboratory "Ekoteks Laboratuvar ve Gözetim Hizmetleri" (https://www.ekoteks.com/). This laboratory is one of only three facilities in Turkey approved by the General Directorate of Public Health of the Ministry of Health and holding a Biocidal Product Analysis Authorization Certificate. The test was performed using the Purification Unit Method (ISO 15714:2019 / GB 21551.3–2010 / ISO 16000–36:2018), including tests for SARS-CoV-2 and other microorganisms. This method evaluates the biocidal properties of air purifiers/disinfectors that do not contain chemical active ingredients, focusing on their effectiveness against airborne microorganisms within specific product groups.

A nebulizer system was used to generate a bacterial aerosol which was then introduced into a 30 m^3 test chamber. Sampling was performed at three intervals: before the air sterilization process, and 30 and 60 min after initiation. Test results are detailed in Table 2.

In addition, the virucidal efficacy tests for the UV-C LED component of the APVS, designed for closed ventilation and air conditioning systems, were developed by modifying the ISO 15714 and BS EN 16777 standard test methods. These methods, which are recognized by the Turkish Ministry of Health, require manufacturers to provide evidence to support their microbial reduction claims. Specifically, the device must achieve a minimum 4-log reduction within 1 h for Influenza (H1N1) virus, Bacteriophage (E. coli), and Serratia marcescens. A logarithmic reduction indicates that the number of bacteria killed significantly exceeds the number of new cells produced, resulting in a rapid decline in the number of bacteria.

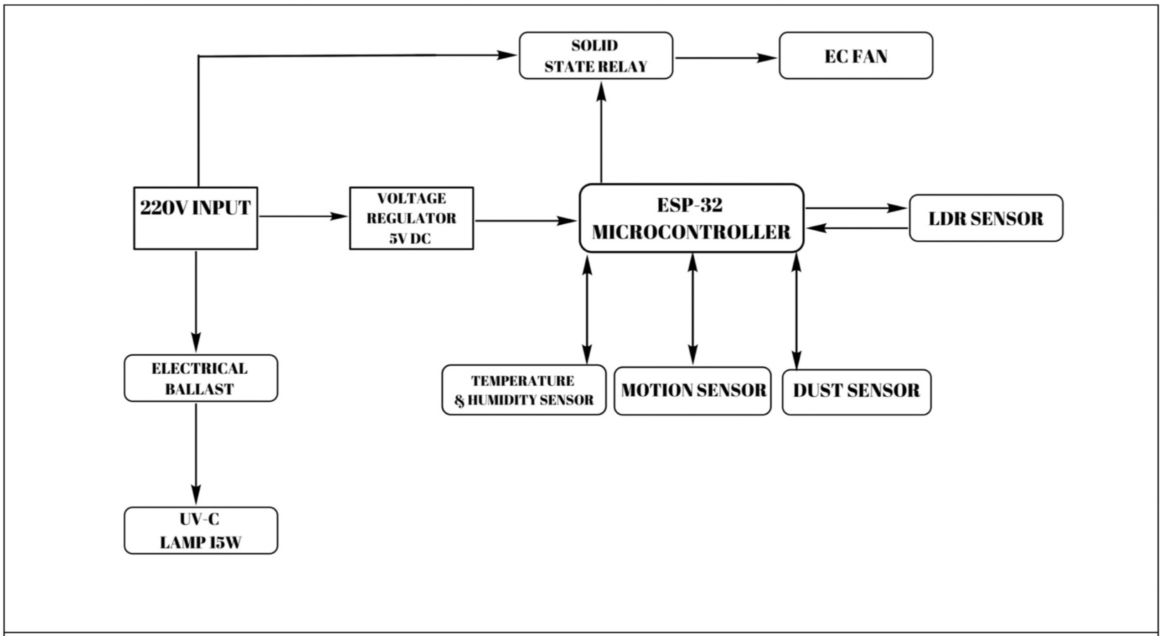
Results: The results showed an impressive filtration capacity (log reduction) of 99.99 % (SD±0.2) for the microorganism and an average decrease with Log= 4.11 for 60 min, highlighting the effectiveness of the developed technological approaches. Log reduction refers to the degree of reduction in the number of microorganisms (e.g. viruses).

3.2. *Air Quality & airborne infection & energy control case study: evaluating the benefits of the proposed adaptive system*

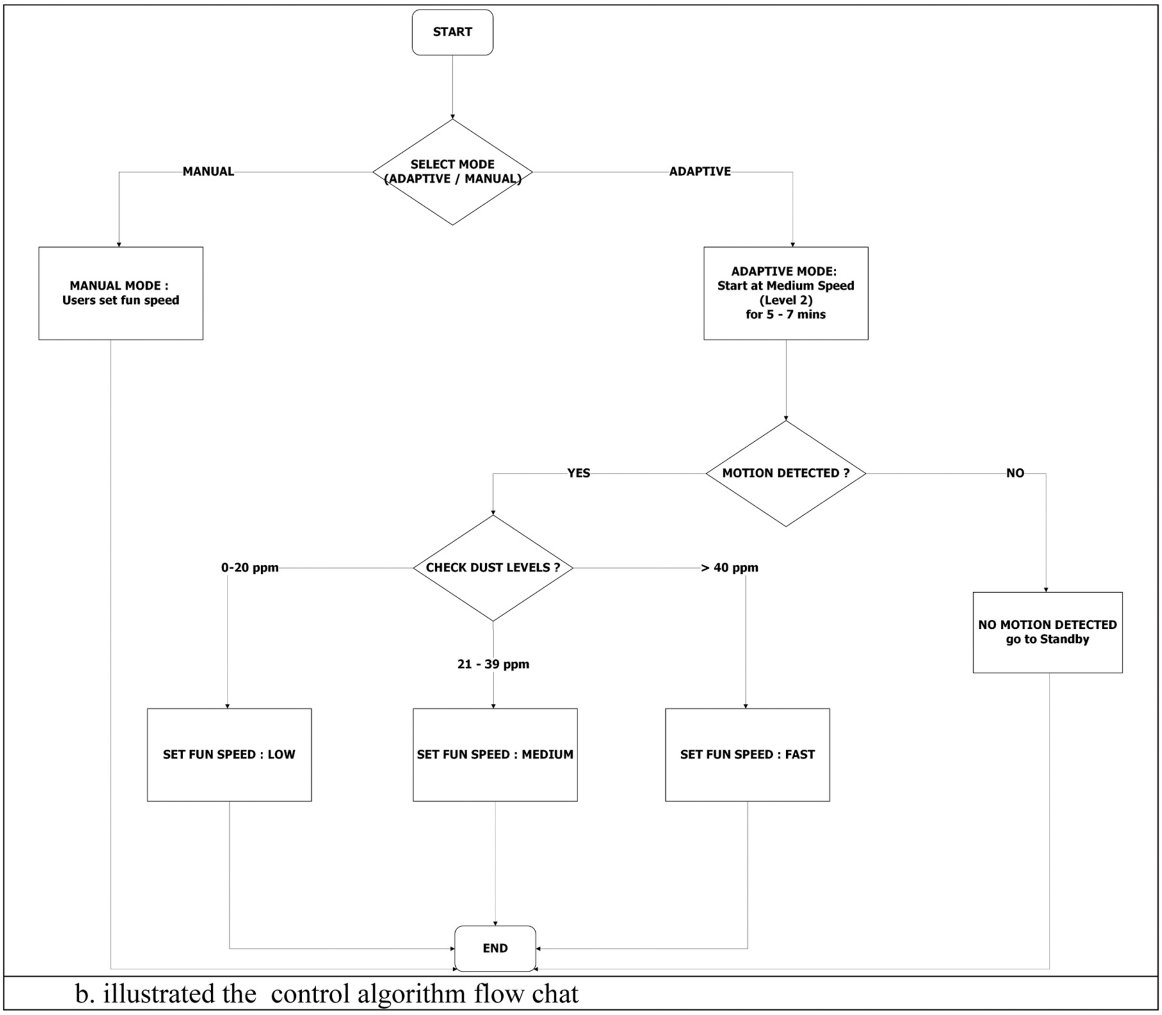
This section presents a comprehensive case study on the resilience of air quality in the built environment from micro to macro scale in a public administration building with a staff occupancy of 14 people. The study conducted a meticulous comparison of air resilience and energy consumption between the APVS and three conventional air ventilation units, using a specific building model that has the following specific data: Total usable area: 800 m2; Ceiling height: 3 m; Total indoor area requiring air purification: 390 m2; Total volume requiring air purification: 1170 m3 (calculated based on a ceiling height of 3 m).

The steps followed in the analysis are outlined below:

- Building Model: Building information includes evidence of room sizes, occupancy levels, and other pertinent details.
- APVS Characteristics: Technical characteristics of the APVS to calculate the estimated energy consumption for the given building model.
- Conventional air handling unit research: information about a conventional air handling unit with similar capacity and efficiency and its technical specifications.
- Calculate the estimated energy consumption for maintaining a resilient indoor environment using all analyzed air handling units based on the given building model.
- Calculation and evaluation and conclusion: Compare the air exchange efficiency (AEE) and energy consumption data for maintaining a resilient indoor environment obtained for 2 equipment systems and analyze the efficiency differences.



a. The electronic diagram and all sensors flow chart diagram of the APVS



b. illustrated the control algorithm flow chat

Fig. 3. a. The electronic block diagram of the APVS and the flowchart of all sensors are shown in a. The system is powered by the 220 V AC city grid and operates in switching mode. The ESP32 microcontroller and sensors are regulated to 5 V DC by a voltage regulator to ensure proper operation. Users can manually select the desired speed and duration. In addition, based on motion sensor input, the unit's operating levels can be automatically adjusted for optimal performance. In addition, the system's closed-loop design provides adaptive speed control and improved energy efficiency. b) The control algorithm is illustrated in the flowchart.

Table 2
Test results after against Serratia Marcescens ATCC 14756 bacteria after 30 and 60 min.

Number of Reproducing Bacteria	Control Group (A)	Air Sterilization Device (B)	Average Decrease
After 30 min			
Number of Bacteria (kob/L)	5.505 × 10ˆ4	1.5 × 10ˆ2	> 99 %
Logarithm Evaluation	4.74	2.11	Log = 2.63 The air sterilization device showed a 2.63 logarithmic reduction against Serratia Marcescens ATCC 14756 bacteria after 30 min.
After 60 min			
Number of Bacteria (kob/L)	45,000	0	> 99.99 %
Logarithm Evaluation	4.65	-	Log = 4.11 The air sterilization device showed 4.11 logarithmic reduction against Serratia Marcescens ATCC 14756 bacteria after 60 min.

3.3. Building model

Our research was conducted in a public administration building with four floors, an average floor area of 200 square meters, and a cumulative usable area of 800 square meters. (Fig. 4a-b). Each floor operates as an open office space, with the ground floor covering 150 square meters (excluding common use areas). The first and second floors consist of open offices of 120 square meters each, excluding designated areas for toilets and storage. In particular, the fourth floor serves as a kitchen and rest area, reserved for temporary use without air purification by any device in this zone. The total indoor area requiring active air purification measures is 390 square meters. With a standard ceiling height of 3 m, the total volume of the building requiring air purification is 1170 cubic meters.s

Because the building does not have central air conditioning (HVAC), the frequency of equipment use varies depending on the floor plan and the efficiency of the equipment in terms of power and performance. The figure shows the ground floor layout of the public building. Specifically, the ground floor office section covers an area of approximately 150 m2. Our design, which is highlighted in green and has air outlets in four directions, is ideally positioned in the center of the office to facilitate air circulation within approximately one hour. The concise details of the air purification requirements for specific areas, as derived from the provided floor plan (Fig. 4), have been compiled and presented in Table 3.

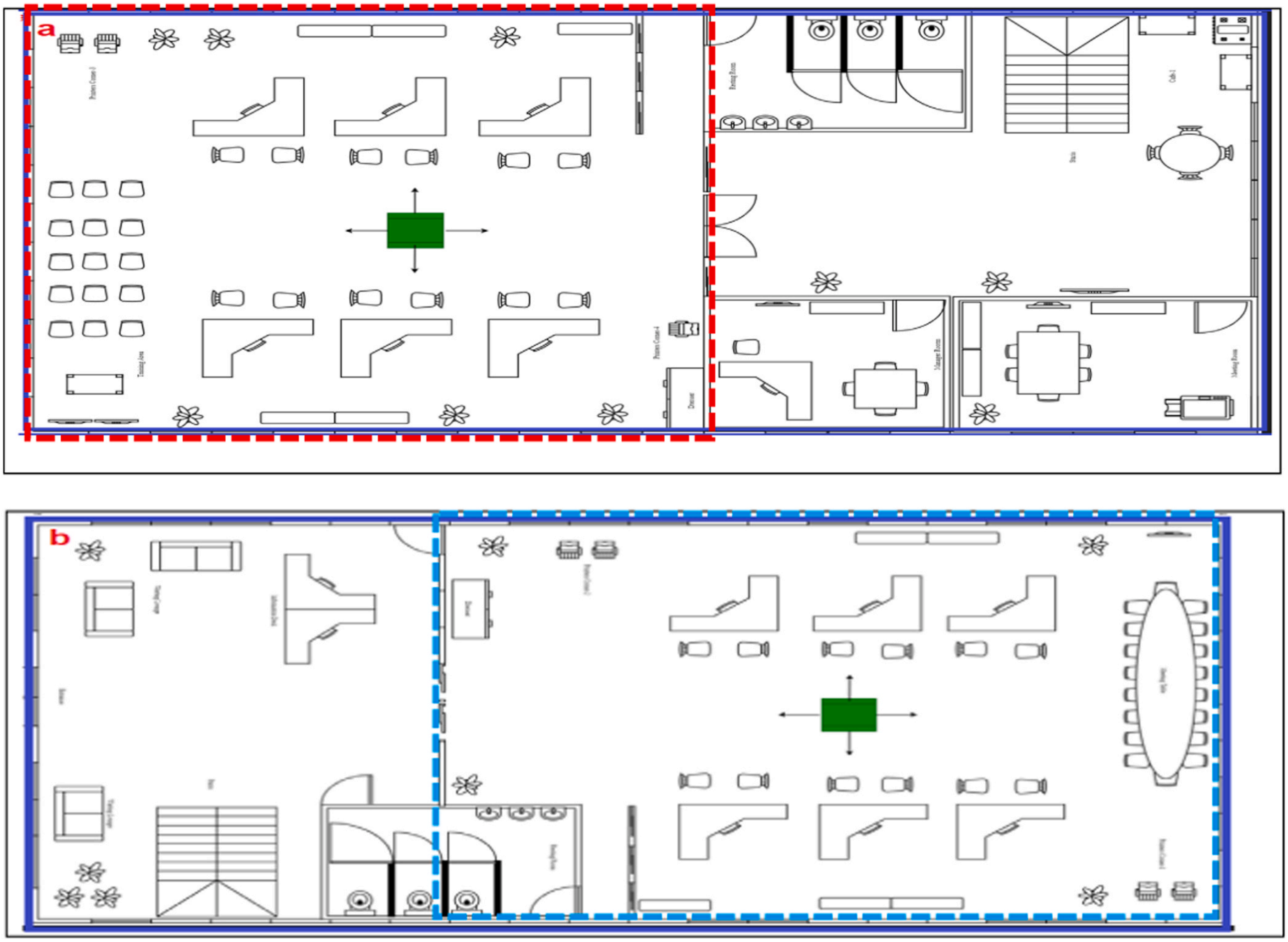


Fig. 4. (a) shows the layout of the 2nd and 3rd floors of the administration building. The red hatched area, approximately 120 square meters, is similar on both floors. Fig. 4(b) shows the floor plan of the ground floor, where the green box indicates the placement of the APVS. The blue hatched area represents 150 square meters, which is the size of the ground floor. The border color is used to differentiate the office space boundaries. The plan does not reflect the actual dimensions, but is scaled proportionally to represent the actual office space and equipment dimensions.

Table 3
The details of air purification needs for specific areas.

Building floors	Functionality (excluding toilets and warehouses)	Indoor Area Requiring Air Purification:
Basement	Not specified for air purification.	Not specified for air purification
2nd Floor	Open offices, each with an area of 120 m2	Average of 200 m2 per floor
3rd Floor	Open offices, each with an area of 120 m2	Average of 200 m2 per floor
4th Floor	Dining and rest hall (total an area of 150 m2)	Temporary use without air purification
Total Indoor Area	Requiring Air Purification:	390 m2
Total Volume	Requiring Air Purification	1170m3(based on 3-meter ceiling height)

3.4. Characteristics of the APVS

Given the volumetric capacity of the APVS of 1750 m3 per hour, the targeted air cleaning area on the ground floor is 150 m2 with a sectional volume of 450 m3. Given its linear operating function, our system achieves approximately 3.9 times the air circulation rate within this targeted area. This means that in a hypothetical scenario where an airborne particle bypasses the filters, it would encounter a 120 W UV-C lamp approximately 3.9 times in one hour. Such a dosage underscores the remarkable sterilization efficacy inherent in the APVS system. In addition, TiO2-coated filters play a key role in the generation of hydroxyl (OH) compounds, which facilitate the degradation of viruses and volatile organic compounds through their photocatalytic effect. The integration of these filters provides versatility by allowing the use of HEPA filters independently or in combination with larger pore HEPA filters. This combination increases the overall purification efficiency against viruses such as SARS-COV-2 and volatile organic compounds (VOCs) (Risbeck et al., 2022).

Taking into account the total volume of the building and the number of units used on each floor, the average air circulation rate of our units per hour is 4.48. This indicates the efficient air circulation and cleaning capabilities of our systems throughout the various zones of the building. In terms of power consumption, APVS operates efficiently in an organization that operates 9 h a day. Utilizing a motion-sensitive sensor, APVS autonomously goes into standby mode when inactivity or lack of motion is detected. This innovative feature not only maintains air resilience, but also contributes to approximately 30 % energy savings, demonstrating the improved energy efficiency of the system.

3.5. Research on conventional ventilation units

In order to illustrate the effectiveness of our APVS unit, we conducted a comparative evaluation of its functionalities with three different air ventilation devices from reputable brands recognized worldwide for their use. These devices are referred to in our evaluation as Unit 1, Unit 2 and Unit 3. Their technical specifications are shown in Table 4

Table 4
The technical specifications of all devices compared.

Air Unit	Fan Power (Wt)	HEPA Filter	Photocatalytic Activity	UV-C lamp (Wt./h)
APVS	150 W	H13	İncluded - TiO2	15
Unit 1 (Carrier CAP 6006)	60 W	E−10	İncluded - TiO2	10
Unit 2 (ALARKO AAP)	30 W	E−10	None	None
Unit 3 (TOSHIBA-CAF)	38 W	None	None	None

3.6. Comparative analysis

In our evaluation of three different devices besides APVS, we compared their technical specifications. APVS operates at 150 watts, while the other units operate at 60 watts, 30 watts, and 38 watts, respectively. Notably, APVS incorporates an H13-type HEPA filter, which is specifically designed for medical filtration (European Committee for Standardization, 2019), while the other devices use F-type HEPA filters, which are intended for more general purposes.

H13 filters are known to cause high pressure drops, requiring the use of more powerful fans to effectively counteract these drops. Based on this data, we continued our comparison and found another significant difference: only APVS and Unit 1 are equipped with a titanium dioxide-based photocatalytic filter, while the other two units lack this component. Regarding the effectiveness of the photocatalytic treatment, we can say that: APVS integrates eight UV-C lamps, each with a power of 15 watts, for a total of 120 watts. On the other hand, Unit 1 is equipped with two UV-C lamps of lower power, 10 watts each, for a total of 20 watts. The UV-C technology, similar to the UV-C systems used in hospitals, purifies air and surfaces through existing ventilation systems. This technology actively kills viral and bacterial pathogens, along with odors, mold and mildew, using safe levels of naturally occurring hydrogen peroxide. The enhanced air purification system provides protection against the spread of viruses and is effective against SARS-CoV-2, the virus responsible for COVID-19. The other two units (Unit 3 and Unit 4) do not utilize UV light capabilities, so we compared APVS to Unit 1 only.

Based on energy consumption, air cycling efficiencies, and other previously provided information, we calculated the estimated energy consumption for maintaining air resilience and cycling efficiencies for the APVS and Unit 1 within the specified building area. (Table 5).

Unit 1, with an efficiency of 510 m3/h, theoretically covers an area of 170 m2 per average hour. However, factors such as the occupancy of the area, traffic, entrances, exits, the output of the UV-C lamp within the unit, and its lower emission require the use of 2 units on each floor. While a single unit will achieve an air cycle approximately every hour, this frequency alone is not sufficient to meet the stringent standards for medical grade sterilization. By opting for 2 units per floor, a total of 6 units are expected to be used in 3 different areas. Consequently, with 9 h of use, the cumulative power consumption reaches 4.32 kW. The lack of stop-start control means that energy saving features are not available. Therefore, the total conversion rate for the 6 units used in the entire building is 2.61.

3.7. Evaluation

For the comparative analysis presented in Table 6, the parameters were calculated using a general methodology and common, simple formulas. Descriptions of these formulas are provided in the nomenclature section. The APVS system offers superior performance and efficiency compared to Unit 1, making it a more effective and cost-effective solution for air purification. Table 6 below shows the advantages of the APVS over Unit 1.

The following key technical parameters were compared and analyzed between APVS and Unit 1:

1. Higher Air Exchange Efficiency (AEE): APVS has an AEE of 0.88, which is significantly higher than Unit 1's AEE of 0.6. This means that APVS exchanges more air per kilowatt of energy consumed, indicating higher efficiency. Let's note that the efficiency is represented by a feature score of 4.49/5.1, with 88 % indicating the performance level. To measure the performance of our experimental studies, the Air Exchange Efficiency (AEE) was determined by calculating the ratio of the air cycles performed in one hour to the total volume divided by the total power consumption. This proportional value provides a clear indication of the efficiency of the system.Total Unit Air Cycles per Hour / Total Volume

Table 5
Technical specification of APVS with Unit 1.

UNIT	Effective Volume	Energy Consumption for maintaining air resilience: Continue 09:00–18:00 for 1 unit	Saving Energy By Human Sensing	Required Device for the Building	Total Consumption	Total Device Air Cycling per hour / Total Volume
	m3/h	kW	kW	pieces	kW	
APVS	1750	2.43	0.73	3	5.1	4.49
Unit 1	510	0.72	0	6	4.32	2.61

Table 6
Unit 1 and APVS performances.

Criteria	APVS	Unit 1	Benefits of APVS
Air Exchange Efficiency (AEE)	0.88 (kW per cycle)	0.60 (kW per cycle)	Higher efficiency; maintains air resilience; cycles more air per unit of energy consumed
Total Unit Air Cycling per Hour	4.49 units	2.61 units	Higher air cycling rate
Total Energy Consumption	5.1 kW	4.32 kW	Slightly higher energy use, but more efficient overall
Energy Consumption per Volume of Air Purified	0.001388 kW/ m^3	0.001412 kW/ m^3	More energy-efficient per m^3 of air purified
Effective Volume	1750 m^3 /h	510 m^3 /h	Purifies a larger volume of air per hour
Adjusted Energy Consumption (with savings)	1.7 kW	Not applicable	Significant energy savings due to adaptive sensing
Adjusted Energy Consumption per Volume	0.000971 kW/ m^3	Not applicable	Further improved efficiency with adaptive technology

2. Better Air Cycling Rate: APVS cycles 4.49 units of air per hour, while Unit 1 cycles only 2.61 units. This higher air cycling rate contributes to better air purification.
3. More energy efficient per unit volume: APVS consumes 0.001388 kW per cubic meter of purified air, while Unit 1 consumes 0.001412 kW per cubic meter. This shows that APVS is more energy efficient per unit volume of air purified.
4. Greater effective volume: APVS can purify 1750 cubic meters of air per hour compared to Unit 1's 510 cubic meters per hour, allowing it to handle larger spaces more effectively.
5. Significant energy savings: With adaptive sensing technology, the APVS saves 0.73 kW, reducing its adjusted energy consumption to 1.7 kW. This adaptive feature ensures that energy is used more efficiently, further increasing cost savings.
6. Lower adjusted energy consumption per volume: The adjusted energy consumption per cubic meter for APVS is 0.000971 kW, demonstrating further improved efficiency due to its energy-saving technology.

In summary, based on the calculations and data presented in Tables 3–6, it is clear that the APVS outperforms other systems available on the market. It excels not only in maintaining a resilient indoor environment and effective energy management, but also in terms of efficiency and performance.

4. Conclusion

The COVID-19 pandemic has highlighted the critical importance of indoor air quality. While ducted systems provide effective solutions, their high installation costs make portable systems a more accessible alternative for improving indoor air quality. However, energy consumption remains an ongoing challenge for existing systems.

In this study, we introduced the APVS device as a state-of-the-art solution for maintaining an antiviral indoor air environment. The APVS system combines air purification and ventilation automation with adaptive fan control driven by motion and dust sensors. By dynamically adjusting ventilation levels based on real-time data - such as population density - it optimises air quality while efficiently managing energy use. Empirical evidence from our case study demonstrates the efficiency and effectiveness of the APVS system in a real-world environment. Implemented in a four-store public administration building with an indoor area of 390 m^2 (total 1170 m^3) to be cleaned, the APVS system achieved an average air circulation rate of 4.48 times per hour throughout the building. On the ground floor, the system provided approximately 3.9 air changes per hour, ensuring comprehensive air purification. The integration of UV-C lamps and TiO_2 coated filters further enhanced the purification by effectively degrading viruses and VOCs through photocatalysis. In addition, the system achieved significant energy savings by reducing power consumption by 30 % through its motion-sensitive standby mode. These results highlight the potential of the APVS to maintain high air quality standards with minimal energy consumption. The APVS achieved a log4 level of air cleaning, meaning that the rate of bacterial death exceeded the rate of new bacterial cell production, resulting in a rapid reduction in bacterial populations. In addition, it achieved significant energy savings of 0.000971 kW/m^3 in tests conducted to ISO 15714 and BS EN 16777 standards, highlighting its energy efficiency. This study has certain limitations that should be noted. In Turkiye, testing for COVID-like viruses is limited to Serratia marcescens in biological testing laboratories approved by the Turkish Ministry of Health. Another limitation is the testing environment. The system was tested in an open office environment, specifically in engineering design offices in Ankara, which typically measure approximately 120 m^2. Performance tests were not conducted in significantly larger spaces, so the results cannot be generalised to larger environments. Looking ahead, we see a wide range of potential applications for our work across different sectors, with the system evolving into different designs to meet specific needs. The APVS can be modularised, providing flexibility for both larger and smaller installations, making it suitable for personal applications and smaller spaces. Future improvements could include increasing the number of sensors and integrating artificial intelligence or machine learning algorithms into the control system, which could lead to further advances in energy efficiency. In addition, future research could focus on evaluating the performance of the APVS in real time in different types of buildings (such as hospitals, schools and industrial facilities) and testing the effectiveness of the system under different climatic conditions. These efforts will help to improve the adaptability and performance of the system in different environments.

CRediT authorship contribution statement

Bunyatova Ulviye: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Kocak Onur:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Data curation.

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.

Data Availability

Data will be made available on request.

References

Bakhtiari, A.R., Zakaria, M.P., Yaziz, M.I., Lajis, M.N.H.L., Bi, X., 2014. Environment Asia. EnvironmentAsia 7 (1), 104–111.

Belussi, L., et al., 2019. A review of performance of zero energy buildings and energy efficiency solutions. J. Build. Eng. 25. https://doi.org/10.1016/j.jobe.2019.100772.

Benito, P.A., Ramírez, C.P., Viccione, G., Lepore, E., 2021. Ventilation for residential buildings: critical assessment of standard requirements in the COVID-19 pandemic context. Built Environ. 7, 1–10. https://doi.org/10.3389/fbuil.2021.656718.

Bian, Y., Fu, X., Gupta, R.K., Shi, Y., 2024. Ventilation and temperature control for energy-efficient and healthy buildings: a differentiable PDE approach. Appl. Energy 372. https://doi.org/10.1016/j.apenergy.2024.123477.

Bourezgui, A., Kacem, I., Karyaoui, M., Chtourou, R., 2016. Optical and photocatalytic properties of porous TiO2 thin films. Optoelectron. Adv. Mater. Rapid Commun. 10 (9–10), 732–736.

Broujeny, R.S., Madani, K., Chebira, A., Amarger, V., Hurtard, L., 2021. A heating controller designing based on living space heating dynamic's model approach in a smart building. Energies 14 (4), 1–25. https://doi.org/10.3390/en14040998.

Carlos, J., Gonzalez, L., Soutullo, S., Aguilera, P., Vi, C., 2020. A bioclimatic building in Madrid: Analysis of the thermal response and long-term comfort indices review. Dev. Built Environ. 3 (June). https://doi.org/10.1016/j.dibe.2020.100015.

Cui, X., Mohan, B., Islam, M.R., Chou, S.K., Chua, K.J., 2017. Energy performance evaluation and application of an air treatment system for conditioning building spaces in tropics. Appl. Energy 204, 1500–1512. https://doi.org/10.1016/j.apenergy.2017.03.067.

Drgoňa, J., et al., 2020. All you need to know about model predictive control for buildings. Annu. Rev. Control 50 (September), 190–232. https://doi.org/10.1016/j.arcontrol.2020.09.001.

Kim, S.E., Park, J.C., Song, Y.W., 2023. Indoor pollutant reduction performance of different mechanical ventilation filters in apartment buildings. Indoor Air 2023. https://doi.org/10.1155/2023/8867880.

Lepore, E., Aguilera, P., Pi, C., 2021. Indoors ventilation in times of confinement by SARS-CoV-2 epidemic: a comparative approach between Spain and Italy 72 (December 2020). https://doi.org/10.1016/j.scs.2021.103051.

Lindblad, M., Tano, E., Lindahl, C., Huss, F., 2020. Ultraviolet-C decontamination of a hospital room: amount of UV light needed. Burns 46 (4), 842–849. https://doi.org/10.1016/j.burns.2019.10.004.

Melikov, A.K., Ai, Z.T., Markov, D.G., 2020. Intermittent occupancy combined with ventilation: an efficient strategy for the reduction of airborne transmission indoors. Sci. Total Environ. 744, 140908. https://doi.org/10.1016/J.SCITOTENV.2020.140908.

Moghadam, T.T., Ochoa Morales, C.E., Lopez Zambrano, M.J., Bruton, K., O'Sullivan, D. T.J., 2023. Energy efficient ventilation and indoor air quality in the context of COVID-19 - a systematic review. Renew. Sustain. Energy Rev. 182, 113356. https://doi.org/10.1016/J.RSER.2023.113356.

Morawska, L., et al., 2020. How can airborne transmission of COVID-19 indoors be minimised? Environ. Int. 142, 105832. https://doi.org/10.1016/J.ENVINT.2020.105832.

A.N. Nair, P. Anand, A. George, and N. Mondal, Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19. The COVID-19 resource centre is hosted on Elsevier Connect, the company ' s public news and information, no. January, 2020.

Narla, S., et al., 2020. The importance of the minimum dosage necessary for UVC decontamination of N95 respirators during the COVID-19 pandemic. Photodermatol. Photoimmunol. Photomed. 36 (4), 324–325. https://doi.org/10.1111/phpp.12562.

Ren, C., et al., 2023. Intelligent operation, maintenance, and control system for public building: Towards infection risk mitigation and energy efficiency. Sustain. Cities Soc. 93, 104533. https://doi.org/10.1016/J.SCS.2023.104533.

Risbeck, M.J., Bazant, M.Z., Jiang, Z., Lee, Y.M., Drees, K.H., Douglas, J.D., 2022. Quantifying the tradeoff between energy consumption and the risk of airborne disease transmission for building HVAC systems. Sci. Technol. Built Environ. 28 (2), 240–254. https://doi.org/10.1080/23744731.2021.1984171.

Schieweck, A., et al., 2018. Smart homes and the control of indoor air quality. Renew. Sustain. Energy Rev. 94 (July), 705–718. https://doi.org/10.1016/j.rser.2018.05.057.

Staszowska, A., 2020. Air purification in sustainable buildings Oczyszczanie powietrza wewnętrznego w budynkach zrównoważonych. Probl. Ekorozwoju 15 (2), 245–252.

Toro, R.G., Diab, M., de Caro, T., Al-Shemy, M., Adel, A., Caschera, D., 2020. Study of the effect of titanium dioxide hydrosol on the photocatalytic and mechanical properties of paper sheets. Materials (Basel) 13 (6). https://doi.org/10.3390/ma13061326.

Vakiloroaya, V., Samali, B., Fakhar, A., Pishghadam, K., 2014. A review of different strategies for HVAC energy saving. Energy Convers. Manag. 77, 738–754. https://doi.org/10.1016/J.ENCONMAN.2013.10.023.

Yue, Z., et al., 2006. Chemically activated carbon on a fiberglass substrate for removal of trace atrazine from water. J. Mater. Chem. 16 (33), 3375–3380. https://doi.org/10.1039/b606679h.

Zhou, Y., et al., 2021. In situ generation of nano TiO2 on activated carbon fiber with enhanced photocatalytic degradation performance. Res. Chem. Intermed. 47 (9), 3769–3784. https://doi.org/10.1007/s11164-021-04490-y.