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Review

A Systematic Review on the Application of Ultraviolet Germicidal Irradiation to HVAC Systems

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Abstract: With the renewed focus on indoor air quality (IAQ) due to "Sick building syndrome" and the recent COVID-19 pandemic, the availability of innovative components and innovative guidance for maintenance and systemic safety design will play an important role, with HVAC systems as protagonists. UV-C irradiation has been investigated for a long time, and some system solutions are known. The aim of this work is to provide an overview of the latest outcomes related to the innovative components of HVAC systems using UV-C irradiation and investigate the current state of the art. A procedure based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was adopted, and the Scopus database was used to query the relevant literature. A total of 66 publications qualified for inclusion in the survey: 29 articles report experimental investigations, 24 articles are related to numerical or theoretical analysis, and both approaches were used in 13 articles. Many papers deal with upper-room UVGI, AHUs, and ducts. A few papers analyse mobile devices. The evaluation of the dose, as in the case of the definition of irradiance, is reported in a small number of articles. This lack of information makes the scenario imprecise and non-quantitative.

Keywords: UV-C radiation; HVAC systems; UVGI; indoor air quality; systematic review

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1. Introduction

The indoor air quality in living and working environments is of paramount importance for human and animal health. The risk of airborne transmission is particularly significant indoors, as human occupancy remains one of the primary sources of bioaerosols. Consequently, poor indoor air quality can facilitate the spread of various pathogens present in the atmosphere [1,2]. In addition, antibiotic resistance represents a significant obstacle to healthcare safety. Therefore, especially during the spread of SARS-CoV-2, both recent and historical research has been conducted on the use of the antimicrobial action of ultraviolet radiation against viruses, bacteria, and fungi.

Technologies based on ultraviolet germicidal irradiation (UVGI) are proving to be effective measures in disinfecting air, water, and surfaces to prevent disease transmission [3].

The use of ultraviolet-C (UV-C) radiation ($220 < \lambda < 280$ nm) has been shown to be one of the most efficient methods for inactivating a wide range of microorganisms and viruses, including SARS-CoV-2 [4]. Exposure to UV-C radiation inactivates microbiological organisms such as bacteria, fungi, spores, and viruses through a purely physical process, without involving chemical reactions. This occurs because the radiation is absorbed by molecules in the cell nucleus, altering the molecular structure of the DNA bonds. In particular, the primary mechanism of inactivation occurs when the absorption of a photon leads to the formation of adjacent pyrimidine dimers on the same DNA or RNA strand (T-T dimers are more common in bacteria, and U-U dimers are more common in RNA viruses) or the formation of a dimer with a single covalent bond, rendering the microorganism incapable of replication. In addition, covalent bonds can be created between proteins and DNA by photo-crosslinking, while the migration of pyrimidines and the breakage of DNA/RNA filaments are less common events that require very high doses [5].

The UV germicidal effectiveness depends on the exposure time, intensity, wavelength, protective particles, and microorganism resistance. For a constant UV power density (W/m^2) exposure, the survival of microorganisms decreases exponentially with time, following different survival curves (typically with one or two tail shapes, as in [6–8]). Radiant exposure (H_0) in J/m^2 is the integral of irradiance over time, often called fluence or dose in the scientific literature, and the value of this parameter required to kill a number of microorganisms depends on the microorganism sensitivity, "k", according to CIE 155:2003 standards [9].

The typical dosages required to kill 90% of most bacteria and viruses range from 2000 to 8000 (μW·s)/cm^2 [10].

Ultraviolet radiation can be used to purify the air in mechanically ventilated spaces within buildings by installing the technology either directly in the HVAC system, particularly in ducts, upstream or downstream of air treatment equipment such as coils and filtration systems, or directly in the room using wall-mounted and/or ceiling-mounted installations or the use of mobile devices. In the first case, greater control over the UV dose is ensured, directly affecting the effectiveness of technology. With regard to the use of devices directly installed or placed in the room, the effectiveness of the technology is highly dependent on the ventilation present to ensure the effective exposure of the particulates to radiation.

It follows that UVGI installed directly in the room provides localised disinfection, whereas the use of the technology in the HVAC system treats the air throughout the entire affected building.

Considering the potential of this technology and given the extensive amount of published material, the aim of this study is to review the relevant scientific literature on the actual application of UV technology in the field of air conditioning and the effectiveness and impact of the design features of this technology in preventing the proliferation of microorganisms on the surfaces of system components and in the indoor air. The proliferation of Colony-Forming Units and the growth of biofilm on the components can not only promote the contamination of indoor air and surfaces but also lead to the deterioration of these components, resulting in increased energy demand from the air conditioning system.

To the best knowledge of the authors, this is the first systematic review conducted with this objective.

The information gained from this study and the review of the state of the art could help determine the utility of UV radiation as a stand-alone or complementary technology to reduce the spread of viral and bacterial diseases while seeking to identify optimal configurations and sources that can ensure both effective microbial action and energy efficiency.

2. Materials and Methods

The use of ultraviolet radiation to sanitise the air and the elements of HVAC systems is of growing interest, especially in environments where air quality is a concern, such as hospitals or industrial environments.

A systematic review of the use of ultraviolet radiation as a sterilising agent to improve air quality was carried out in accordance with the PRISMA guidelines [11]. As is well known, this method of reviewing the open literature is proposed to ensure exhaustive research, clearly delimited by the defined inclusion and exclusion criteria, and to provide an impartial and objective analysis for conclusive findings, avoiding bias.

In particular, for this research, the electronic database SCOPUS was used, where a combination of keywords was employed to identify relevant studies with the help of Boolean operators. More specifically, the following keywords were linked by the operator "OR": "UV", "UVC", "ultraviolet", "ultra violet", "ultra-violet", "ultraviolet rays", "UV light", "UVC light", "ultraviolet germicidal irradiation", UVGI, "germicidal UV radiation"; those keywords were linked by the operator “AND” to the following keywords, again linked by the operator “OR”: “indoor air quality”, “IAQ”, “air quality”, “room purification”, “room disinfection”, “room sanitization”, “room sanification”, ”confined space*”, air purification”, “air purifier*”, “air disinfection”, “air sanitization”, “air sanification”, “air conditioning”, “HVAC”, “air handling unit”, “AHU”, “air channel*”, “air duct*”.

For this study, any research that used mathematical or computational models and experimental tests to investigate the effectiveness of ultraviolet radiation was considered appropriate.

As mentioned above, a structured procedure was followed to select the articles. First, a preliminary identification phase was carried out on the basis of the exclusion criteria using the titles of the publications. This was followed by a second phase (screening step), in which the research abstracts were carefully evaluated in order to identify the eligible papers according to the criteria of interest. Finally, the studies that were considered relevant based on the analysis of the abstracts were selected for a full reading of the manuscript.

Specifically, the following inclusion and exclusion criteria were defined and applied through the steps of identification, screening, and inclusion to select the studies of interest for the review, which were finally analysed in detail.

Inclusion criteria:

- The documents must include UVC sources and/or an HVAC system.
- The germicidal effectiveness of the device and/or the installation configuration must be evaluated.
- The research must examine the effects of ultraviolet radiation as part of the process of air quality improvement or the treatment and maintenance of the HVAC system.

Exclusion criteria:

- The articles deal with water and surface disinfection.
- The aim is to assess the effects on humans.
- The studies involve pathogens that were previously grown in the laboratory and exposed directly to lamp irradiation.
- The language is not English.

The preliminary studies do not prove the effectiveness of UVC radiation experimentally or numerically but only provide guidelines for future research.

A period of 10 years was chosen to give priority to more recent research, and only English-language papers were selected.

The division of tasks involved an initial phase in which each of the three authors independently carried out the selection of the relevant material, followed by a second phase in which all three authors reviewed all studies.

In cases of doubt, the senior author made the final decision.

3. Results

In the identification phase of the research, a total of 1805 articles were initially analysed, of which 800 were non-duplicates and 1005 were excluded. The exclusion criteria were then applied to reduce the selection to 65 articles that met the previously outlined inclusion criteria.

As shown in Figure 1, from a total of 800 initial articles, $N = 517$ were excluded because they did not meet the inclusion criteria on the basis of their abstracts alone. This resulted in a final sample size of $N = 283$. After reading the full texts of these papers, a further $N = 49$ were excluded due to the unavailability of the full text, and $N = 169$ were excluded because they met the exclusion criteria mentioned above.

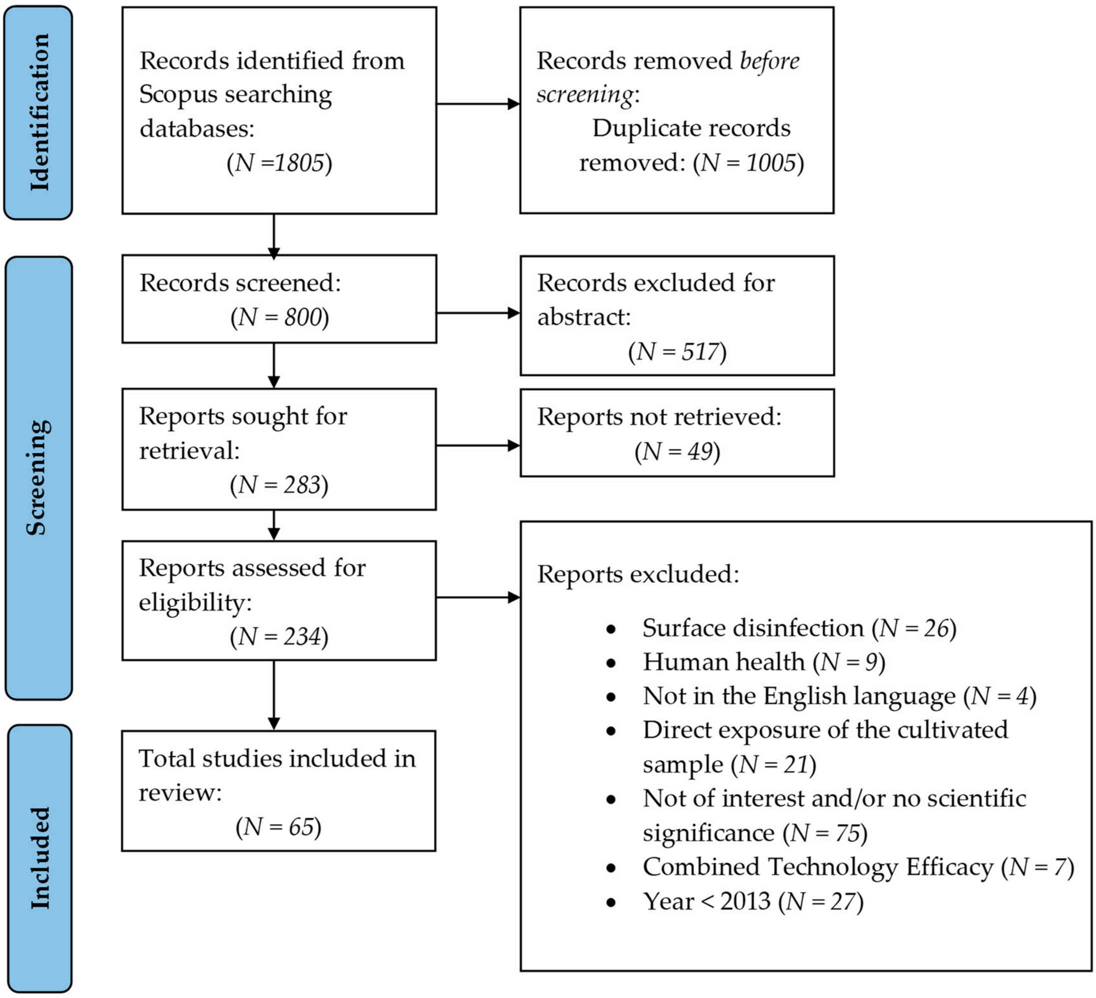

Figure 1. PRISMA flowchart for studies included in this review.

The 65 included articles are summarised in Table 1.

Table 1. Summary of the study methodologies included in this review (Ref. = Reference; I = first author; Y = year; C = country; Num = numerical study; Exp = experimental study; Inst = installation typology).

Ref.	I	Y	C	Num	Exp	Inst
[12]	Al-Rawi, Mohammad	2021	USA		Two restaurant spaces	In ceiling and upper zone of the room walls
[13]	Al-Rawi, Mohammad	2022	New Zealand		Bedrooms	A mobile device
[14]	Anderson, Deverick J.	2013	United States		Hospital rooms	A mobile device
[15]	Arora, Akhilesh	2023	India	Statistical structural and fluid dynamics simulations of prototype	Test chamber	A mobile device
[16]	Atci, Fatih	2021	Turkey	CFD and radiation simulations		In duct

Table 1. *Cont.*

Ref.	I	Y	C	Num	Exp	Inst
[17]	Baldelli, Giulia	2022	Italy		Train HVAC system	AHU and duct
[18]	Bang, Jong-Il	2018	South Korea	UV intensity distribution and CFD simulations	Upper area of the negative-pressure isolation ward	Upper-room UVGI
[19]	Brockmann, Gerrid	2023	Germany	UVC-LEDs irradiation and CFD		In duct
[20]	Bui, Cuong Mai	2023	China	CFD and irradiance model	Ventilated test chamber with aerosol source and UV lamps	In duct and ceiling
[21]	Capetillo, Azael	2014	United Kingdom	CFD and UV dose simulations		In duct
[22]	D'Orazio A.	2020	Italy		Test AHU	AHU
[23]	Davidson, Bruce L.	2021	New Zealand		Office room	Upper-room UVGI
[24]	De Matteis, Ludovic	2022	France	Ray tracing		A mobile device
[25]	de Souza, Susana Oliveira	2022	Brazil		Intensive care unit	In duct
[26]	Feng, Zhuangbo	2021	China	UV field, CFD simulations of a filter prototype		In duct
[27]	Firrantello, Joseph	2018	United States	Theoretical benefit–cost analysis of UV coil cleaning		AHU
[28]	Gilkeson C.A.	2014	United Kingdom	CFD and radiation simulations		Upper-room UVGI
[29]	Glyva, Valentyn	2023	Ukraine		LED lamps in test room	Upper-room UVGI
[30]	Hsu, Lin-Hang	2022	Taiwan	CFD and radiation simulation	Test chamber	Upper-room UVGI
[31]	Jones, Hugh L.	2022	United States		Surgery room	Mobile device
[32]	Kanaan, Mohamad	2015	Lebanon	CFD model of pathogen-carrying particles	Fully controlled CC/DV test room	Upper-room UVGI
[33]	Kanaan, Mohamad	2015	Lebanon	Mathematical modelling of flow, CO_2, and bacterial concentration for a plume multi-zone multi-layer model	Test chamber	Upper-room UVGI
[34]	Kanaan, Mohamad	2019	Lebanon	CFD simulation of recirculation flow		Upper-room UVGI
[35]	Kanaan, Mohamad	2014	Lebanon	Mathematical modelling of bacterial distribution in a CC/DV for the plume multi-zone multi-layer model	Test chamber	Experimental CC/DV room
[36]	Kotov, Mikhail A.	2022	Russian Federation	Ray-tracing simulation	Test cylindrical cavity	Test cylindrical cavity

Table 1. *Cont.*

Ref.	I	Y	C	Num	Exp	Inst
[37]	Kouropoulos, Giorgos	2021	Greece	Mathematical model of pathogen inactivation by radiation		In duct
[38]	Krishnamoorthy, Gautham	2016	United States	CFD and radiation simulation	Patient room	A mobile device
[4]	Lai, Po-Yen	2021	Singapore	Ray tracing	Experimental setup for measuring the radiation profile of the UV-C LED light source	Upper-room UVGI
[39]	Lee, Bruno	2013	United States	A mathematical model of microorganism inactivation		AHU
[40]	Lee, Linda D.	2022	United States		Six sites in the same building	Upper-room UVGI
[2]	Li, Peiyan g	2022	United States		Dirty test chamber (particulate matter air filtration prototype and UV-C light	In duct
[41]	Liu, Jiatao	2022	China	Ray tracing through a filter		In duct
[42]	Luo, Hao	2022	Canada	Ray tracing and CFD		In duct
[43]	Luongo, Julia C.	2016	United States		Cooling coil surfaces	AHU
[44]	Luongo, Julia C.	2017	United States		Cooling coil surfaces	AHU
[45]	Mariita, Richard M.	2022	United States	Ray-tracing simulation	UVC-LEDs in test chamber	Duct device
[46]	Messina, Gabriele	2020	Italy		Operating room	Mobile device
[47]	Noakes, Catherine J.	2015	United Kingdom	Mathematical model (zonal, mixing model)		Upper-room UVGI
[1]	Nunayon, Sunday S.	2022	China		UV-LED in test chamber	Upper-room UVGI
[48]	Nunayon, Sunday S.	2020	China		UV-LED in test chamber	Room UVGI
[49]	Nunayon, Sunday S.	2020	China		UV-LED and mercury-vapour lamps in test chamber	Room UVGI
[50]	Pan, Yue	2022	Viet Nam	UV radiation of a vertically cylindrical UV lamp		In room
[51]	Pichurov, George	2015	Bulgaria	CFD simulation		Upper-room UVGI

Table 1. *Cont.*

Ref.	I	Y	C	Num	Exp	Inst
[52]	Qiao, Yuechen	2021	United States		Three low-pressure UV–C Hg lamps, aligned parallel to the flow	In duct
[53]	Randive, Rajul	2022	United States	Airflow and radiation fluence rate simulation	Prototype in a test chamber	Vehicle cabin AHU
[54]	Rudnick S.N.	2015	United States		Bacterial inactivation in a test chamber	Upper-room UVGI
[55]	Ruwan Jayakantha D.N.P.	2022	Sri Lanka		Experimental setup	UV device air filter
[56]	Singh, Dilpreet	2023	United States		A class II A2 biosafety cabinet	Upper-room device
[57]	Song, Li	2020	China		In ambulance	Device
[58]	Srivastava, Shubham	2021	United States	CFD and infection risk simulations		A mobile device
[59]	Vijeta	2021	India	A mathematical model about cosine correction for irradiance measurements		Upper-room UVGI
[60]	Wang M.H.	2023	China		Full-scale chamber (2.30 m × 2.25 m × 2.30 m).	Room UVGI, robot, in duct, in HVAC
[61]	Wang, Can	2019	China		Experimental setup to verify the inactivation efficiency and rate of three different UV sources	A mobile device
[62]	Wang, Shan-Ni	2019	China		Hospital blood sampling rooms	A mobile device
[63]	Wang, Yi	2016	Singapore		Cooling coil	AHU
[64]	Xie, Yankai	2023	China		Two full-scale ventilation systems for air disinfection tests	In duct
[65]	Yang, Yi	2018	China	CFD and UV-radiation simulations with reconstructed model	UVC installation	In duct
[66]	Yang, Yi	2016	China	A mathematical model based on a view-factor approach		Upper-room UVGI
[67]	Yang, Yi	2021	China	CFD and radiation simulations		In duct

Table 1. *Cont.*

Ref.	I	Y	C	Num	Exp	Inst
[68]	Yang, Yi	2019	China	Mathematic model	UVC lamp installation	In duct
[69]	Yarahmadi	2023	Iran	CFD and radiation simulations	Isolated chamber unit connected to the treatment part	Disinfection treatment device
[70]	Yildirim, Gülşah	2021	Turkey		UVGI fan systems	Upper-room UVGI
[71]	Zhang, Huihui	2022	China		A laboratory test rig was built to quantify the disinfection performance of UVC irradiation	In duct
[72]	Zhu, Shengwei	2014	China	CFD simulation of ceiling fan and ultraviolet irradiation system		Upper-room UVGI
[3]	Zhu, Shengwei	2022	United States	CFD simulation with UR-UVGI		Upper-room UVGI

In the following, some details of the objectives, methods, and results of the included articles are given.

3.1. Included Articles

Al-Rawi et al. [12] demonstrate the efficacy of unshielded upper-room germicidal ultraviolet-C lamps with irradiance measurements in two setups, indicating a cost-effective system but emphasising the importance of airflow evaluations.

Al-Rawi et al. [13] studied a portable air filter UV dehumidifier in a non-heated bedroom compared to a heat pump room. The PFUV dehumidifier, with a low-cost HEPA filter and UV irradiation, effectively reduced airborne particles, including mould spores, particularly in the older bedroom.

Anderson et al. [14] tested automated UV-C lamps in 39 patient rooms. A significant reduction in various populations was found after UV-C treatment.

Arora et al. [15] developed a low-cost solar-powered air purifier and showed that the prototype effectively neutralised bacteria and mould within 30 min of operation.

Atci et al. [16] studied a UV-C lamp array for in-duct UVGI by performing CFD simulations with four lamp configurations, evaluated the differences in velocity and irradiance distributions between the cases, and reported the disinfection rates.

Baldelli et al. [17] tested a UV-C LED and ioniser air disinfection system for trains. Effective bacterial inactivation was observed at all airflow speeds, with UV-C playing a significant role, while filters and ionisers alone were insufficient.

Bang et al. [18] evaluated the effectiveness of a UR-UVGI system in controlling airborne microorganisms in isolation wards and adjacent areas by performing air sampling, UV intensity calculations, and simulations with different placements, intensities, and airflows.

Brockmann et al. [19] studied near-UVC irradiation in ventilation systems for air decontamination in occupied spaces. CFD simulations showed that the efficiency of air decontamination depends on the airflow velocity, inlet–outlet distances, chamber size, and baffle placement.

Bui et al. [20] improved a model for a CFD-based assessment of bioaerosol dispersion and UV disinfection. Experiments in a ventilated chamber showed that the modified irradiance model accurately predicted the bioaerosol dispersion and UV disinfection of influenza A virus.

Capetillo et al. [21] used CFD to evaluate the UV lamp placement in a duct for the airborne-particle UV dose, with optimal results achieved with the lamp alignment on both axes. The average UV dose did not directly correlate with the sterilisation efficacy due to the complex relationships and mechanisms, and the sterilisation effects remain unclear.

D'Orazio et al. [22] investigated the effect of UVC on HVAC systems. The results showed that the irradiation of HEPA filter surfaces was effective in reducing microbial contamination, especially at humidity levels below 60%.

Davidson [23] investigated a UVGI light–dehumidifier with two types of filters to reduce PM2.5 levels and improve indoor air quality. The most effective combination was UV lights with the Dual-10 30/30 Camfil filter, which reduced the PM2.5 levels and relative humidity.

De Matteis et al. [24] improved UVC robot irradiance models and validated them with empirical data. Wave propagation and energy diffusion models were considered, taking into account reflective surfaces and custom UVC lamp housings.

De Souza et al. [25] tested UVC equipment in a COVID-19 ICU HVAC system for microbial inactivation. The results showed significantly fewer colonies in the UVC-disinfected air, confirming the effectiveness of UVC.

In Feng et al. [26], numerical modelling was used to evaluate a UV + Filter system and two electrostatic cleaning systems (ESP and HEFS). The results showed that the UV + Filter system achieved 100% efficiency against SARS-CoV-2 aerosols and 100% filtration for particles in the [0.1 μm, 2.5 μm] range.

Firrantello et al. [27], in a simulation study of a UVGI system used for coil cleaning, showed that the cost savings in illness prevention exceeded the energy costs, with the effectiveness influenced by factors such as the outdoor air fraction and economiser use.

Gilkeson et al. [28] simulated an upper-room UVGI system in a naturally ventilated hospital ward and improved its design by using CFD analysis and numerical optimisation. The results show that mounting fixtures at low levels on the leeward side of the ward provides the best coverage and facilitates the interaction between patients and disinfected airflows.

Glyva et al. [29] experimentally investigated the use of LED UV radiation for air ionisation and indoor surface disinfection in occupied spaces, assessing the safety distance of LED UV-C systems and the reduction in microbial contamination.

Hsu et al. [30] developed a cyclone-structured device for enhanced air purification with UVC light and measured an 89% reduction in bacterial concentration during testing.

Jones et al. [31] compared surgical-site contamination rates during active surgery with and without UV air disinfection systems. The results showed no statistical difference in contamination rates between the two groups, with the main variables affecting contamination rates being the number of staff present and the size of the operating theatre.

Using experiments and CFD, Kanaan et al. [32] evaluated a mathematical model for Controlled Contaminant/Dilution Ventilation (CC/DV) rooms with upper-room ultraviolet germicidal irradiation (UVGI) to assess airborne disease transmission and "droplet"-mode infections. The results showed that CC/DV systems with upper-room UVGI effectively protected against both modes of transmission.

Kanaan et al. [33] used a 3D CFD model to analyse airflow, thermal patterns, CO_2 levels, and bacterial dispersion in a test chamber equipped with upper-room UVGI. The results showed that UVGI is crucial for energy efficiency and indoor air quality, especially in the case of higher recovery rates.

Kanaan [34] optimised HVAC systems using CFD modelling for return-air ratios and upper-room UVGI integration. Simulations in a typical office space showed that a 37% return-air ratio and an 18 W UVGI system met the WHO bacterial limits, reducing heating energy consumption and maintaining IAQ in the breathing zone.

Kanaan et al. [35] developed a multi-layer bacterial transport model for CC/mixed DV rooms with upper-room UVGI and validated it by performing CFD simulations. Upper-room UVGI improved the return airflow, optimising energy efficiency while maintaining air quality.

Kotov et al. [36] enhanced germicidal UV radiation by using diffuse reflective materials in UV air purifiers. Experiments showed a significant enhancement of the radiation flux. A flux enhancement formula was derived and numerically validated. The study discussed potential applications in UV air purifiers.

Kouropoulos [37] investigated the population of live pathogenic microorganisms in air sterilised using a UVGI lamp in a closed air duct. The results showed that the percentage of inactivation of pathogenic microorganisms by UV-C irradiation varied exponentially with the Reynolds number of the airflow.

Krishnamoorthy et al. [38] optimised portable UVGI technology using radiation modelling. Radiometric measurements of UV-C irradiance and CFD simulations were performed. Reflective coatings to enhance UVGI were tested in a hospital room. The predictions were accurate close to the lamp but varied on distant surfaces due to ray effects, mitigated by reflection. The average radiation increased by 60% in the coated rooms.

Lai et al. [4] developed a UV-C LED ray-tracing simulator for SARS-CoV-2 inactivation in public spaces, compared the results with those of Zemax OpticStudio, and validated the simulator using experimental UV-C LED radiation profiles. Inactivation coefficients for SARS-CoV-2 were derived. The simulator helped to optimise UV-C system placement for maximum sterilisation.

Lee et al. [39] investigated the efficiency and cost-effectiveness of an in-duct UVGI system within a VAV system. Taking into account the air temperature and velocity, the study shows that installing the UVGI system at the mixed-air location offers cost savings and improved performance.

Lee et al. [40] evaluated the effectiveness of fixed UVGI air cleaners in high-occupancy commercial indoor spaces. Using air, surface, and swab sampling, they found that these systems achieved significant reductions in both airborne and surface microbial contamination.

Li et al. [2] improved air filtration with UV-C lamps to effectively neutralise airborne pathogens, especially SARS-CoV-2. They refined UV-C dose calculations and performed radiation tests. The results showed that the "filtration + UV" prototype achieved over a 99% reduction in airborne bacteria at both high and low airflow rates, outperforming the "filtration only" and "UV only" configurations. The latter configurations also showed significant reductions in bacterial counts.

Liu et al. [41] investigated a 3D air filter combined with UV light for air disinfection. Numerical simulations were performed to analyse the light penetration, and experimental tests were conducted using *E. coli*. The 3D filter allowed the efficient penetration of UV light into the inner layers, effectively inactivating microorganisms.

Luo et al. [42] developed a mathematical model to predict in-duct bioaerosol disinfection systems using a view-factor approach and CFD simulations for different configurations of UV lamp radiation and duct materials. Highly diffuse reflection from the duct walls resulted in a more uniform UV irradiance distribution, improving bioaerosol disinfection for in-duct UVGI devices.

Luongo et al. [43] measured microbial counts on cooling coils and in the air, comparing irradiated and non-irradiated coils under different operating conditions. Surface and air samples were collected. UV and drying reduced the microbial load, especially in humid conditions.

In Luongo et al. [44], UVG on a cooling coil was found to increase heat transfer under condensing conditions in mild climates, with no significant difference under dry conditions. Static pressure drops were unchanged.

Mariita et al. [45] aimed to establish a dose–response curve for a surrogate for SARS-CoV-2 and to evaluate the integration of UVC into car HVAC systems. The UVC LEDs imply a rapid reduction in the population in the cabin.

Messina et al. [46] evaluated the impact of a mobile air filtration unit on the air quality in an operating theatre during bariatric surgery and reported a significant reduction in particle concentration during surgery when the unit was in use.

Noakes et al. [47] proposed a numerical model to assess the infection risk and energy consumption of upper-room UVGI devices in interconnected spaces such as hospital wards. The model takes into account zonal mixing, UV fields, and microbial degradation and shows that upper-room UV systems can be more efficient compared to increasing ventilation rates.

Nunayon et al. [1] developed a novel rotating upper-room UVC-LED device for the effective inactivation of indoor pathogens. The results showed the effectiveness of the device under different flow and dose conditions.

Nunayon et al. [48] evaluated the efficiency of a UR-UVGI-LED system in inactivating airborne bacteria under different conditions and measured the UV susceptibility of the bacteria. The results showed an effective reduction in the concentrations of several species of airborne bacteria.

Nunayon et al. [49] compared the disinfection efficacy of a novel UR-UVGI-LED system with a conventional UR-UVGI-MV system. UV irradiance measurements and bioaerosol sampling were performed. The results show the potential advantages of UR-UVGI-LED systems.

Pan et al. [50] performed 3D numerical simulations of the UV irradiation field for different lamp powers and identified sterilised zones for different microorganisms.

Pichurov et al. [51] evaluated the effectiveness of an upper-room UVGI system with a rotating fan against different microorganisms using CFD simulations. The effectiveness increased with the fan, especially at lower speeds.

Qiao et al. [52] developed a high-flow UV–C duct system for efficient virus inactivation and evaluated the effectiveness of a compact UV–C flow tube reactor in a custom-built wind tunnel. The results showed a remarkable reduction in virus concentrations, especially at lower flow rates.

Randive et al. [53] evaluated the effectiveness of UVC LEDs and reflective materials in the HVAC system of a vehicle for bioaerosol disinfection. The experimental and numerical results showed a significant reduction in virus particles in the vehicle air.

Rudnick et al. [54] assessed the effect of a ceiling fan on the effectiveness of upper-room UVGI using two bacteria as test aerosols. The results showed that the ceiling fan can reduce the effectiveness of upper-room UVGI if the air turnover rate falls below 66 times per hour.

Jayakantha et al. [55] designed an air purifier using UV light and an electric field. The results showed that UV radiation alone was ineffective in reducing bacterial counts, the electric field alone resulted in a significant reduction, and the combination of UV radiation and the electric field significantly reduced bacterial counts.

Singh et al. [56] evaluated the inactivation effectiveness of four commercial devices based on UV and blue light against a surrogate for SARS-CoV-2. The results showed that 254 nm and 275 nm hand-held devices effectively inactivated the virus on surfaces, and a ceiling-mounted 222 nm UVC device was effective against airborne viruses.

Song et al. [57] validated a pulsed-xenon UV device for real-time air disinfection in ambulances using air sampling and CFU counts. The study found a reduction in *E. coli* and Staphylococcus albus within 30 min, demonstrating the effectiveness in real-world settings.

Srivastava et al. [58] evaluated the risk of SARS-CoV-2 infection with different ventilation systems. Computational modelling evaluated mixed ventilation, outside air intake, and UV-C units, and the results showed that mixed ventilation and UV-C units were effective in reducing the risk of infection.

Vijeta et al. [59] carried out mathematical modelling and theoretical simulations for practical lighting scenarios. The results emphasised the importance of cosine correction in calibrated detectors and showed that multiple light sources distributed across the ceiling could provide more uniform illumination within an enclosure compared to a single central light source.

Wang M.H. et al. [60] experimentally evaluated the efficacy of far-UVC (222 nm) combined with ventilation to reduce the risk of indoor airborne pathogen infections using aerosolised bacteria and air sampling.

Wang et al. [61] compared UVD, UVC, and UVA sources in the inactivation of aerosolised *E. coli* by collecting bioaerosol and endotoxin samples. The results showed that UVC and UVD were more effective than UVA. In particular, UVD produced ozone, which removed both free and bound endotoxins, whereas UVC and UVA did not. Endotoxin transformation during UV irradiation was also observed.

Wang et al. [62] evaluated the effectiveness of non-thermal atmospheric plasma and PX-UV by collecting air samples in hospital blood-sampling rooms. Both methods significantly reduced airborne bacterial concentrations, including nosocomial pathogens such as Staphylococcus aureus.

Wang et al. [63] investigated the effect of UV irradiation on cooling coil performance in hot and humid conditions. The results showed improved thermal conductivity (+10%), a reduced pressure drop (−13%), and reduced fan energy consumption (−9%) over ten months, outweighing the cost of the UV lamp by 39%.

Xie et al. [64] developed a bioaerosol control strategy for ventilation systems using UV irradiation and microstatic electricity. The results showed the effectiveness of UV under certain conditions. The combination of UV 254 with microstatic electricity showed high efficiency, outperforming UV 254 alone. The approach was cost-effective, with low energy consumption and a minimal pressure drop, suitable for HVAC-driven pathogen disinfection in building ventilation systems.

Yang et al. [65] evaluated the performance of an in-duct air purifier with different bacteria and flow rates using a 10 W UVC lamp. The results showed effective disinfection for most bacteria, with *S. epidermidis* being the most resistant. A numerical Eulerian method confirmed effective in-duct UVGI disinfection at lower velocities.

Yang et al. [66] used a mathematical model and numerical simulation to evaluate the effectiveness of multiple upper-room UVGI devices with different placements, quantities, microorganism susceptibilities, fluence rates, and air-exchange rates. Higher air-exchange rates reduced microorganism exposure to UV, with a more significant effect at lower rates (2.9 ACH) and a decreasing effect at higher rates (6 ACH).

Yang et al. [67] evaluated an in-duct UVGI system using CFD and irradiation simulations for the inactivation of *Escherichia coli*, *Pseudomonas alcaligenes*, and *Salmonella enterica*. The results show that almost 100% disinfection was achieved for a specific Reynolds number range.

Yang et al. [68] developed a new mathematical model based on the view-factor approach to predict in-duct UV lamp irradiance and validated it using a 254 nm UV detector. The model works better for UV lamps with short tubes and is useful for describing UV lamp performance in ducts with limited interference from diffuse reflections.

Yarahmadi et al. [69], using CFD simulations with radiation, collected respiratory droplets and evaluated the effectiveness of a specially designed slotted hood, taking into account geometric and aerodynamic factors, to reduce the risk of virus spread in intensive care units under real-life operating conditions.

Yildirim et al. [70] evaluated microbial air contamination in CT scanning rooms and the effectiveness of shielded UV-C arrays. The results showed significant microbial contamination and the effectiveness of two 15W UV-C LED arrays in eliminating this contamination, even in the absence of ventilation or air conditioning.

Zhang et al. [71] evaluated the disinfection performance of far-UVC (222 nm) irradiation on bioaerosols in full-scale duct flows. The results showed no significant difference in the inactivation of the bioaerosols tested between 222 nm and 254 nm UV irradiation.

Zhu et al. [72] evaluated the effect of ceiling fan rotation on air mixing and the effectiveness of an upper-room UVGI disinfection system using a rotating-reference-frame CFD method. The method accurately reproduced the fan-induced airflow and vertical air mixing caused by the ceiling fan.

Zhu et al. [3] developed a CFD method to analyse air recirculation, filtration, and UR-GUV air disinfection with exhaled aerosols. The results suggest that the ceiling height affects the effectiveness of UR-GUV by influencing air mixing and UV exposure. High ceilings benefit from UR-GUV, potentially reducing the need for increased filtration or outdoor air for infection control. In rooms with low ceilings, UR-GUV alone may not be sufficient, indicating the need for additional measures, such as masks.

3.2. Document Distribution over Time

As noted above, this research focused on the last decade. Interest in the use of this technology increased significantly with the advent of the SARS-CoV-2 pandemic. In fact, most of the studies (*N* = 41) were carried out between 2020 and 2023, with 26% in 2022 alone, as shown in the graph in Figure 2.

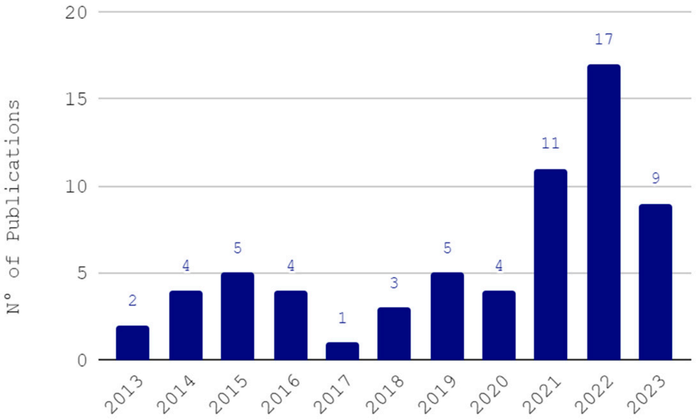

Figure 2. Number of studies published in the last 10 years related to review.

3.3. Research Approaches

Among the selected papers, *N* = 29 were carried out using experimental approaches, while *N* = 21 used numerical approaches, with *N* = 5 using mathematical modelling and *N* = 16 relying on simulations based on finite element theory. In the remaining *N* = 15 of the papers considered, both numerical and experimental analyses are carried out to validate the latter.

3.3.1. Experimental Works

Among the experimental studies [1,2,12–14,17,22,23,25,29,31,40,43,44,46,48,49,52,54–57,60–64,70,71], three [12,13,23] performed tests in work or everyday living environments, while [1,2,15,29,48,49,54,56,60,70] performed tests in test chambers. Some papers [14,17,25,43,44,52,62–64,71] are dedicated to performing experiments in hospital wards or HVAC systems serving the hospital. In [31,46], the focus was sanitation in the operating room.

3.3.2. Numerical and Theoretical Approaches

Of the 65 articles included, *N* = 21 used numerical approaches, with *N* = 5 [37,39,47,59,66] using mathematical modelling and *N* = 16 [3,16,19,21,24,26–28,34,41,42,50,51,58,67,72] using finite elements simulations. More specifically, [24,27,37,39,41,50,59,66] investigated the irradiation field; refs. [34,47,51] are related to CFD simulations; and in [3,16,19,21,26,28,42,58,67,72], both fluid dynamics and radiation aspects are covered.

3.3.3. Theoretical/Numerical and Experimental Approaches

In 15 of the papers considered [4,15,18,20,30,32,33,35,36,38,45,53,65,68,69], both numerical and experimental analyses were carried out to validate the latter. More specifically, refs. [4,36,45,68] investigated the irradiation field; refs. [15,32,33,35] referred to CFD simulations; and in [18,20,30,33,38,65,69], both fluid dynamics and radiation aspects are covered.

3.4. Set Configuration

Regarding the location of the source (Table 1), *N* = 28 [1,3,4,12,15,18,20,23,28–30,32–35,40,47–51,54,56,59,60,66,70,72] involved the use of upper-room UVGI systems installed either on walls or ceilings, while for *N* = 8 articles [22,27,39,43,44,53,60,63], the source was installed directly inside the AHU (air-handling unit), and for *N* = 18 [2,16,17,19–21,25,26,37,41,42,52,60,64,65,67,68,71], the lamps were installed in the ventilation ducts. On the other hand, *N* = 10 articles [13,14,31,38,46,55,58,60–62] reported the use of mobile devices introduced into the rooms for disinfection, while [24,36,45,57,69] dealt with the use of a non-mobile device (*N* = 4), and the rest (*N* = 1) provided an analysis of irradiance measurements.

3.4.1. UVC—Source

In Table 2, the technology used to generate UV-C irradiation is reported.

Table 2. Summary of the source characteristics reported in the articles included in this review.

Ref	Mercury-Vapour Lamp	UVC-LEDs	Pulsed-Xenon Ultraviolet (PX-UV)	Krypton-Chloride Excimer Lamps	Amalgam UV Lamps	Not Reported
[12]	x					
[13]						x
[14]	x					
[15]		x				
[16]	x					
[17]		x				
[18]						x
[19]		x				
[20]						x
[21]						x
[22]	x					
[23]	x					
[24]	x					
[25]	x					
[26]	x					
[27]	x					
[28]						x
[29]		x				
[30]	x					
[31]						x
[32]	x					
[33]	x					
[34]						x
[35]						x
[36]					x	
[37]						x

Table 2. *Cont.*

Ref	Mercury-Vapour Lamp	UVC-LEDs	Pulsed-Xenon Ultraviolet (PX-UV)	Krypton-Chloride Excimer Lamps	Amalgam UV Lamps	Not Reported
[38]	x					
[4]		x				
[39]	x					
[40]	x					
[2]	x					
[41]	x	x				
[42]	x					
[43]	x					
[44]	x					
[45]		x				
[46]	x					
[47]						x
[1]		x				
[48]		x				
[49]		x				
[50]	x					
[51]						x
[52]	x					
[53]		x				
[54]	x					
[55]						x
[56]	x	x		x		
[57]			x			
[58]						x
[59]						x
[60]				x		
[61]	x					
[62]			x			
[63]	x					
[64]	x					
[65]	x					
[66]						x
[67]						x
[68]	x					
[69]						x
[70]		x				
[71]	x					
[72]						x
[3]		x				

The most widely used technology to date is still the mercury-vapour lamp (*N* = 30), characterised by a monochromatic spectrum at 253.7 nm. However, an emerging technology seems to be gaining ground (*N* = 11), namely, UVC-LEDs, characterised by a polychromatic emission spectrum. Other technologies (*N* = 5), such as pulsed-xenon ultraviolet, krypton-chloride excimer, and mercury-amalgam lamps, are also under consideration. Only two articles provide a comparison between technologies. Specifically, [41] compares mercury-vapour lamps with the emerging technology, while [56] does the same with krypton-chloride excimer lamps.

For 18 papers, the source of the application is not specified.

3.4.2. Source Installation

Several authors [3,28,34,47,50,51,59,66,72] evaluated ceiling- and wall-mounted UVGI installations using mathematical models or simulations, while others [1,12,23,29,40,48,49,54,56,60,70] examined similar installations using experimental tests. The authors of [4,15,18,20,30,32,33,35] applied, at the same time, mathematical, theoretical, and experimental studies on upper-room UVGI or non-room configurations.

From reading the above articles, the following findings emerged:

- Fans improve efficiency up to a certain speed;
- The ceiling height influences the UV distribution;
- The UVGI lamp placement and wall type significantly affect disinfection;
- Localised airflow may not completely prevent bacterial transmission, and increased air exchange reduces the microbial exposure time and affects the UV dose.

These findings highlight the importance of a strategic UVGI approach and thoughtful environmental design for infection control. Ventilation remains critical in certain scenarios. In conclusion, UVGI is effective against microbes, with a focus on UV-C LEDs and proper ventilation.

The authors of [27,39] investigated the effectiveness of installing UVGI sources in the AHU using numerical modelling, while the experiments in [22,43,44,60,64] addressed this issue by using an experimental approach, and [53] conducted a study of this configuration using a mixed approach.

The research results show that this technology offers significant benefits in terms of component maintenance, resulting in improved energy efficiency and air quality.

References [16,19,21,26,30,37,41,42,67] focus on the modelling of one or more lamps installed directly in ventilation ducts.

These studies show that the efficiency of air disinfection is strongly influenced by environmental conditions such as humidity and temperature, as well as the airflow dynamics and the installation position of the sources. This is also confirmed by [2,17,25,52,60,64,71], where field experiments were carried out, and by [20,45,68], where the problem was studied by using a mixed approach.

Research has also been carried out on the use of devices (mobile or not), with articles [24,58] addressing the issue from a mathematical perspective, while [2,13,14,31,46,55,57,60,62] studied it from an experimental perspective, and [38,45,69] used a mixed approach.

The literature indicates that the effectiveness of these devices is influenced by environmental conditions and the sensitivity of microorganisms to radiation, as previously observed. It has also been noted that the combination of UVC with other strategies, such as HEPA filters, further enhances disinfection effectiveness. The positioning of UVC sources and the uniform distribution of radiation in the environment are critical factors in the success of UVC disinfection. A strategic approach to positioning can maximise the results. Despite the progress made, further research is needed to fully understand the potential and limitations of UVC technology in different applications and environmental conditions.

A summary diagram of the typologies of the source installations is shown in Figure 3.

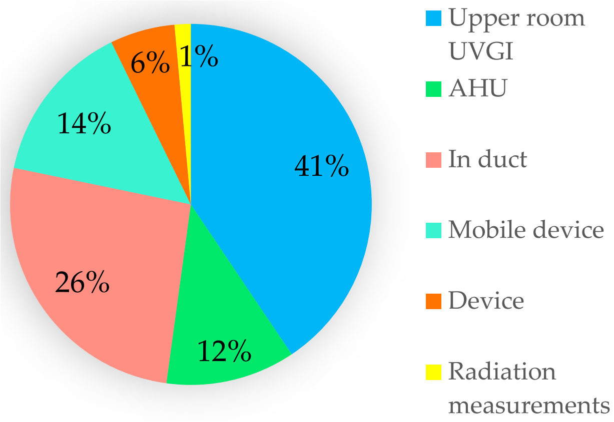

Figure 3. Typologies of the source installations in this review.

3.4.3. Installation Target

Of the 65 studies included in this review, $N = 54$ articles [1,3,4,12–21,23–25,28–38,40,42,45–52,54–62,65–72] aimed to improve IAQ through direct air disinfection, while $N = 11$ articles [2,22,26,27,39,41,43,44,53,63,64] focus on component sanitisation. In particular, $N = 5$ articles [27,39,43,44,63] deal with the sanitisation of batteries installed in the AHU, highlighting how climatic variability, optimal UV lamp placement, and HVAC integration are key factors in the effectiveness of the technology. In addition, economic analyses show how this technology provides an economic benefit as a result of improved component performance due to improved cleanliness. The remaining $N = 6$ articles [2,22,26,41,53,64] deal with both the air and the filtering system in the AHU for direct irradiation. These studies convincingly demonstrate the effectiveness of UV in air and filter disinfection. By optimising UV systems with filters, high particle and germ removal rates can be achieved, reducing the risk of re-aerosolisation. However, specific conditions, such as temperature, airflow, and UV dosage, can also affect the overall efficiency. An economic analysis is required to assess the feasibility of such systems.

3.5. Effectiveness Evaluation

Of the $N = 45$ articles in which the method used is experimental or experimental/numerical, $N = 34$ assess the effectiveness of this technology by taking air samples before and after the activation of the technology under investigation.

In particular, the authors of [1,12,14,22,23,25,30,45,48,56,60–62,64,70] carried out effectiveness tests using air samplers to verify the actual decay.

The results in [15,46] confirm the time required for successful decontamination. In particular, the former study observed initial reductions after 30 min, while the latter study observed a 90% reduction in the first 5 min.

Reference [17] shows a positive result for bacterial decontamination but with less efficacy in fungal reduction.

References [2,20,29,31,57,65] report the percentages of microbiological counts. Depending on the case studied, the use of UV radiation alone as a sterilising agent resulted in a reduction range of 65–90%.

References [18,44,52,54] emphasise that sampling, in addition to confirming antimicrobial efficacy, is fundamental to optimising the final configuration of the installation.

Reference [71] compares the use of 222 nm and 254 nm technology and finds no changes in microbiological reduction.

On the other hand, the authors of [33,55] note the ineffectiveness of UV technology. The first study concludes that the use or non-use of ultraviolet radiation does not alter the contamination rate, but what seems to influence it is the number of occupants and/or the size of the operating theatre under consideration. The second study examines the combination of UV with the electrostatic field and finds that the use of UV alone does not result in a significant reduction in microbiological counts.

3.6. Energy Efficiency

The authors of [1,13,19,22,27,33–35,39,47,48,58,63,64] have not only looked at germicidal efficacy but also devoted part of their work to energy and economic studies, carrying out cost–benefit analyses of the implementation of this new technology in relevant locations. What emerges from these research efforts is that energy efficiency and the effectiveness of air disinfection using UV technologies are common themes. Optimising the placement of UV sources and integrating them with other strategies, such as the use of HEPA filters, can help reduce energy consumption and improve indoor air quality in buildings. However, it is important to consider the specific environmental conditions and carefully evaluate the options available to maximise both energy and health benefits.

3.7. Irradiance–Exposure-Time–Dose

Table 3 reports the technical details of the sources used in each selected study. Specifically, irradiance, exposure time, and dose (defined as the product of the first two variables) are reported.

Table 3. Summary of the irradiation details of the studies included in this review.

Ref	Irradiance (μW/cm^2)	Time (s)	Dose (μJ/cm^2)
[12]	24 μW/cm^2 (without distance)	Not reported	Not reported
[13]	Not reported	Not reported	Not reported
[14]	Not reported	Not reported	Each device was programmed to deliver a reflected dose of 12 μWs/cm^2 for vegetative bacteria (VRE or Acinetobacter) or 22 μWs/cm^2 for spores (C. difficile)
[15]	Not reported	Not reported	Not reported
[16]	Not reported	Not reported	Case 1 (>18.3 J/m^2), Case 2 (>18.49 J/m^2), Case 3 (>19.12 J/m^2), Case 4 (>18.39 J/m^2)
[17]	Not reported	Not reported	3.99 to 10.32 J/m^2
[18]	Not reported	Not reported	Not reported
[19]	Not reported	Not reported	Not reported
[20]	Various, at one and two metres from the source	Not reported	Not reported
[21]	Not reported	Not reported	Various
[22]	480 μW/cm^2 (without distance)	Not reported	Not reported
[23]	Various (volume average and surface average at 1.2 m and 1.8 m from the floor)	Not reported	Not reported
[24]	Not reported	Not reported	Not reported
[25]	(2.7 ± 0.5) mW/cm^2 without aluminium coating; (8.6 ± 0.3) mW/cm^2 with aluminium coating (volume average)	Not reported	Not reported
[26]	Not reported	Not reported	Not reported
[27]	Not reported	Not reported	Not reported
[28]	0.12 W/m^2 (average over the upper zone of the room)	Not reported	Various (depends on ventilation rate and the transformation considered)
[29]	<30 J/m^2 at a distance of two metres	Not reported	Not reported

Table 3. *Cont.*

Ref	Irradiance (μW/cm^2)	Time (s)	Dose (μJ/cm^2)
[30]	Not reported	Not reported	Not reported
[31]	Not reported	Not reported	Not reported
[32]	Not reported	Not reported	Not reported
[33]	12 W/m^2 (without distance)	Not reported	Not reported
[34]	Not reported	Not reported	Not reported
[35]	Not reported	Not reported	Not reported
[36]	Not reported	Not reported	Not reported
[37]	11,699 μW/cm^2 (1st Case), 23,398 μW/cm^2 (2nd Case) 35,747 μW/cm^2 (3rd Case) (without distance)	Not reported	Not reported
[38]	15.7 W/m^2 in the control room and 25.0 W/m^2 in the room with the reflective paint (volume average)	Not reported	Not reported
[4]	Various at [0:0.2:1.6] m from the source	30 s	Not reported
[39]	Not reported	Not reported	Not reported
[40]	Not reported	Not reported	Not reported
[2]	Not reported	Not reported	Not reported
[41]	At 275 nm and 254 nm, values are 31.0 W/m^2 and 30.3 W/m^2, respectively (without distance)	30 min	Not reported
[42]	Various (at measurement points on different frontal planes)	Not reported	Not reported
[43]	200 μW/cm^2 (coil surface average at 25.4 cm from source)	Not reported	Not reported
[44]	200 μW/cm^2 (coil surface average at 30.48 cm from source)	Not reported	Not reported
[45]	12.4 mW/cm^2 (Volume average)	Not reported	40 mJ/cm^2
[46]	Not reported	Not reported	Not reported
[47]	0.2 W/m^2 (surface average at the central plane)	Not reported	Not reported
[1]	0.698–0.673 μW/cm^2 for operating one and two LEDs, respectively	Not reported	Not reported
[48]	0.316 μW/cm^2 (range, 0.160–2.670 μW/cm^2), 0.382 μW/cm^2 (range, 0.210–3.520 μW/cm^2), and 0.517 μW/cm^2 (range, 0.250–5.730 μW/cm^2) for three different input currents (without distance)	Not reported	Not reported
[49]	18.95 μW/cm^2 (measurement average at the same point)	Not reported	Not reported
[50]	100 W/m^2 to around 1 W/m^2 (average surface at y = 1.5 m)	5 s	Not reported
[51]	67 mW/m^2 (without distance)	Not reported	Not reported
[52]	11.17 mW/cm^2 (average over different measurement points)	4.44 s;1.81 s;1.25 s	49.63 mJ/cm^2; 20.28 mJ/cm^2; 13.92 mJ/cm^2
[53]	Not reported	Not reported	0.25 mJ/cm^2

Table 3. *Cont.*

Ref	Irradiance (µW/cm^2)	Time (s)	Dose (µJ/cm^2)
[54]	Various (at measurement points on six different frontal planes)	Not reported	Not reported
[55]	Not reported	Not reported	Not reported
[56]	Various (the treatment surface distance is not specified)	Various	Various
[57]	Not reported	Not reported	Not reported
[58]	Not reported	Not reported	Not reported
[59]	1 W/m^2 (normal incidence point at 3 m from source)	Not reported	Not reported
[60]	0.73 µW/cm^2 (volume average)	Not reported	Not reported
[61]	Not reported	Not reported	Various
[62]	Not reported	Not reported	Not reported
[63]	Not reported	Ten months	Not reported
[64]	Not reported	Not reported	Not reported
[65]	23.7, 6.3, and 2.5 W/m^2 for the 100%, 50%, and 25% luminous length configurations (at y = 1.4 m)	Not reported	Not reported
[66]	Various (at z = 2.44 m height plane)	Not reported	Not reported
[67]	Not reported	Not reported	Not reported
[68]	Not reported	Not reported	Not reported
[69]	Not reported	Not reported	Not reported
[70]	Not reported	Not reported	Not reported
[71]	Not reported	Not reported	Not reported
[72]	48.3 W/m^2 (without distance)	Not reported	Not reported
[3]	0.2 W/m^2 (without distance)	Not reported	Not reported

In Table 3, it is possible to observe the limited number of articles providing data on the irradiance considered, the exposure time to radiation, or, even less frequently reported, the dose, which is a fundamental parameter for evaluating the effectiveness of the technology.

Among the selected articles, only 10 of them, specifically [14,16,17,21,28,45,52,53,56,61], report the parameter related to the dose, while the other 31 provide only the irradiance values considered.

In particular, References [3,12,22,33,37,38,41,48,51,56,72] give irradiance data without specifying the distance and/or the measurement volume or surface as provided by the manufacturer or verified on site. In [4,20,22,23,25,28,29,38,42–44,50,52,54,59,60,65,66], the irradiance data given refer either to the average measured over a specific surface with known coordinates relative to the source or to sampling points over the whole volume of interest.

In [4,50], the dose is not given directly, but the parameter is provided by giving both the irradiance at different measurement points and the exposure time to the radiation itself.

A summary diagram of the irradiation details provided in the included articles is shown in Figure 4.

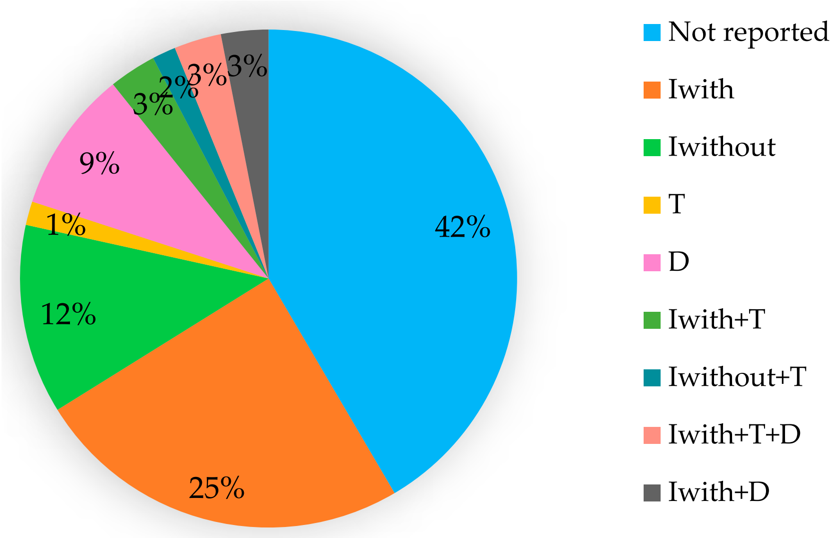

Figure 4. Irradiation parameters provided in the included articles: Iwith = irradiance measured at a certain distance from the source; Iwithout = irradiance value given without distance information; D = dose; T = exposure time.

As mentioned above, with regard to the dose, *N* = 10 articles give the doses used to inactivate the microorganisms observed and the average dose in general cases. Most studies highlight how the dose is directly dependent on the positioning of the lamps, the geometry of the system, and the speed of the airflow.

In particular, References [16,17,21,28] indicate that the position of the radiation source has a strategic impact on the effectiveness of sterilisation. This aspect is of great importance for the definition of the dose in the mentioned cases, which directly depends on the position of the radiation source. References [16,17,28,45] report that the flow conditions, flow rate, and speed have a fundamental impact on the definition of the irradiation dose, with an inversely proportional relationship. References [16,17,56,61] show that the correct design of ventilation systems has a decisive influence on the actual effectiveness of the sterilising action and is directly related to the dose used.

4. Discussion

This systematic review, which focuses on the use of UV-C devices in HVAC systems, highlights two main aspects: the pathogen inactivation capacity of UVC radiation and the lack of guidelines and fundamental aspects for the characterisation of the process from a practical point of view.

The analysis of the included articles shows that UVC radiation can inactivate viruses, bacteria, and fungi. However, since the dose, defined as the incident power density per exposure time, required for inactivation is specific to the type and characteristics of a particular microorganism, systematic research is required to provide useful design support. Several studies, particularly those of a numerical nature, have confirmed that external factors such as relative humidity, ventilation, and temperature significantly influence the effectiveness of ultraviolet radiation.

In detail, the following findings are highlighted:

- Relative humidity has a significant effect on germicidal action, as an increase in humidity leads to a drastic reduction in radiation effectiveness.
- Ventilation has a dual nature, as increasing it, resulting in turbulent flows, will increase the exposure of microorganisms. However, if it is too strong, it may not ensure the appropriate exposure time for inactivation.
- Temperature plays a crucial role, especially in achieving maximum output from light sources.

This review, therefore, highlights the importance of a number of factors, including the positioning of lamps, the type of light source used, the presence of reflective materials that increase incident radiation on surfaces and suspended particles, and airflow and ventilation models.

Despite the positive results found in the literature in the case of installations inside air-handling units (AHUs) for the sanitisation of components, this installation is still relatively uncommon and less studied. Installation in ducts or in the room is preferred, but these options can present problems in terms of dosage due to the high air velocity and the size of the room.

Due to the recent large-scale introduction of new technologies to the market, it is necessary to investigate the effectiveness of the proposed technology. Only about 50% of the articles focus on this issue. Although the dose is a fundamental parameter in the assessment of efficacy, only a few of the 65 included articles provide the actual value used in the case in question. This is probably due to the lack of literature on the characterisation of ultraviolet sources from both experimental and computational points of view, leading to an almost exclusive reliance on manufacturers' specifications, without a unified model that can be applied to all sources and different configurations.

The energy aspect is still neglected. Few studies devote a section of their work to cost–benefit analysis, which, in any case, shows that positive results depend on the thermo-hygrometric conditions of the installation environment and the geometry of the site.

Finally, a cost–benefit analysis should also be carried out in relation to the durability and degradation of materials exposed to UV radiation over long periods of time.

5. Conclusions

In this work, available data on the actual application of UV technology in the field of air conditioning have been collected through a systematic search.

These data provide interesting insights and allow some reflections. UV radiation has a powerful germicidal effect, capable of inactivating a large number of species of microorganisms, such as viruses, bacteria, fungi, and algae.

Antimicrobial activity has mainly been observed in the UVC range at 254 nm (as the older technology for the radiation source is the mercury-vapour lamp), although several studies have examined different wavelengths to provide a comparative pattern.

The germicidal effect of UV light is well known, while the study of its use as a disinfectant in closed environments has yet to be conclusively studied.

In the studies reported in this review, the value of the dose is only reported in a few cases, just as the definition of the irradiance is only reported in a few articles. This lack of information makes the scenario imprecise and non-quantitative. Both experimental and theoretical studies emphasise the disinfecting and germicidal power of ultraviolet radiation, but the factors that influence its effectiveness are many: the speed of the airflow, for example, in HVAC systems, and the flow rate, which determines the exchange of air in a closed environment, are fundamental elements for the real effectiveness of UV radiation. The geometry of the systems, the arrangement of the lamps, and the direction of the airflow also affect the disinfection performance of UV-lamp disinfection systems. These aspects are critical in assessing the dose of radiation delivered to the microorganisms per unit of time.

One of the key aspects that require further investigation is the need to establish comparable measurement setups to ensure the repeatability and consistency of results across different implementations. More specifically, the values of the dose (and/or the irradiance and exposure time values) could be verified in the room or in AHU systems in crucial zones, and the irradiance values emitted by the lamps could be declared with all necessary details (solid of emission for frequency of interest).

In conclusion, the research in this field is constantly evolving, and our study has highlighted the importance of considering a wider range of aspects, including those related to effectiveness, safety, and economic considerations. Through further research, this technology can be further perfected, leading to safer and more effective solutions for environmental disinfection and improvements in people's quality of life.

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