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Review

Microwave irradiation for airborne virus inactivation: Evidence and future perspectives

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SUMMARY

Non-thermal microwave (MW) irradiation has emerged as a promising approach for inactivating airborne viruses by exploiting their vibrational properties through selective resonant energy transfer (SRET). In this narrative review, we synthesize current evidence on the antiviral efficacy of non-thermal microwave (MW) technologies, evaluate their feasibility for indoor infection control, and highlight existing limitations as well as future research directions. A literature search was conducted across PubMed, Scopus, Google Scholar, and ScienceDirect for studies published between January 1, 2015, and March 7, 2025, using keywords related to MW irradiation, SRET, and airborne viruses. The evidence was organized into three key themes: mechanistic foundations of the technology, effectiveness against airborne viruses, and regulatory and safety considerations. The available data indicate that MW irradiation disrupts viral structures through vibrational resonance mechanisms, with effectiveness varying by viral type and depending on optimized frequency and exposure duration. Regulatory authorities recently acknowledged its potential to reduce airborne transmission, contingent on meeting stringent safety standards for electromagnetic compatibility, specific absorption rates, and power density. In summary, non-thermal MW irradiation offers a scalable solution for reducing airborne respiratory virus transmission. Pending further real-world validation, integrating this technology into public health strategies offers a promising approach to strengthen infection prevention and control in both healthcare settings and indoor environments, effectively targeting both human and zoonotic infections.

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Introduction

The COVID-19 pandemic has revived global attention to the airborne transmission of respiratory viruses.[1] Over the past few years, new evidence has emerged regarding aerosol dynamics, leading to a reevaluation of airborne transmission mechanisms – which include both droplet and fomite-based pathways.[2] Emerging research has further emphasized the critical role of aerosol inhalation – defined as the intake of microscopic particles (≤ 5 µm in diameter) that remain suspended in the air for extended periods – as a key mechanism for the spread of respiratory viruses, particularly in shared indoor environments.[3] The COVID-19 pandemic has provided compelling examples of this phenomenon, as superspreading events and indoor transmission patterns frequently eluded explanation by traditional models centered on larger droplets (> 5 µm) or surface contact.[2,4] These findings have sparked an ongoing scientific debate on reassessing infection prevention and control (IPC) strategies, highlighting the unique capacity of airborne transmission to facilitate widespread exposure across both spatial and temporal dimensions.[2,5]

Among emerging technologies for inactivating airborne viruses, non-thermal microwave (MW) irradiation has garnered significant attention as an innovative method that leverages the unique biomechanical properties of virions while preserving the structural integrity of human tissues.[6] Operating within the electromagnetic spectrum range of 300 MHz to 300 GHz, MW irradiation induces targeted mechanical resonance in viral particles through a mechanism known as microwave resonant absorption (MRA).[7,8] This

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phenomenon arises when MW frequencies align with the confined acoustic vibrational (CAV) modes of spherical and rod-shaped virions,[6,9] which are governed by factors such as hydration state, surface charge distribution, and size-dependent vibrational eigenmodes.[6] Recent advancements in selective resonant energy transfer (SRET) technology have further refined this approach by enabling precise frequency matching to the resonance signatures of viral particles.[6,8,10,11] This innovation leverages differences in vibrational properties between pathogens and host cells, allowing SRET to channel MW energy into dipolar CAV oscillations within virions.[6] When the localized stress amplitudes surpass critical thresholds for capsid or envelope integrity, viral particles undergo non-thermal inactivation.[6,10]

In this narrative review, we present the available evidence on the antiviral potential of non-thermal MW irradiation – with a particular focus on SRET technology – for mitigating airborne respiratory virus transmission. With this aim, we examine the underlying mechanisms of action, evaluate efficacy across different viral pathogens, and consider current regulatory frameworks. Furthermore, we explore the practical integration of MW technologies into contemporary IPC strategies, while addressing existing limitations and outlining key research priorities in the field.

Methods

A comprehensive literature search was conducted across four major databases (PubMed, Scopus, Google Scholar, and ScienceDirect) to identify relevant studies on the effects of non-thermal MW irradiation on airborne respiratory viruses. Articles published in English between January 1, 2015 and March 7, 2025 were identified using a strategy that combined the following keywords and Boolean operators: ("microwave" OR "microwave irradiation") OR ("resonant energy transfer" OR "SRET") AND ("airborne virus" OR "respiratory virus" OR "virus") (Table 1). The initial search yielded 304 articles, which were screened based on their titles and abstracts to identify studies specifically addressing the antiviral effects of MW irradiation on airborne respiratory viruses. Full-text articles were retrieved for review, and reference lists of selected studies were manually searched to uncover additional relevant publications. The inclusion criteria covered experimental studies and reviews investigating the effects of MW on viral inactivation, with a particular emphasis on its application to human and zoonotic airborne infections. Papers that did not specifically address airborne viruses, aerosols, or MW-based technologies were excluded. A flow diagram of studies' screening and selection is presented in Fig. 1. Data synthesis was conducted using a two-phase narrative framework. Initially, evidence was compiled and categorized into three main themes: (1) the physical mechanisms driving non-thermal MW viral inactivation, (2) the effectiveness of microwave irradiation in neutralizing airborne viruses, and (3) the current regulatory frameworks governing the practical deployment and safety of these technologies. In the second phase, studies were critically reviewed to assess potential applications of non-thermal MW technologies against common human and zoonotic respiratory viruses, emphasizing their integration into indoor environments for IPC purposes. Future research directions were also identified.

Results

Physical principles underlying non-thermal MW virus inactivation

Non-thermal MW virus inactivation is underpinned by the physical phenomenon of resonance, whereby a system absorbs energy most efficiently when exposed to electromagnetic waves at its natural vibrational frequency and wavelength.[6,13] This process is mediated by SRET, which enables the coupling of electromagnetic energy to CAVs within viral particles.[6–12] Specifically, these resonant oscillations generate mechanical stress that can deform or rupture the viral envelope or capsid, ultimately compromising the structural integrity of the virion.[6] In enveloped viruses – characterized by a lipid bilayer embedded with viral proteins – this effect is particularly pronounced, as core-shell oscillations between the inner and outer structures produce opposing forces capable of fracturing the membrane.[6,9,10] The resonance frequency required for effective viral inactivation is primarily determined by the virus's biophysical properties – including particle size, elasticity, and shape.[6,13] In general, larger viruses resonate at lower frequencies, whereas smaller viruses require higher frequencies for efficient energy absorption. For instance, influenza A virus (93 nm) has been shown to resonate around 12 GHz, whereas enterovirus-71 (40 nm) resonates near 44 GHz.[6] Environmental factors may further modulate resonance efficiency.[6,7] Acidic conditions, for example, can modify zeta potential and surface charge distributions, resulting in changes to resonance frequency and a decrease in MRA efficiency.[6,8] Moreover, the presence of viscous aqueous media may attenuate mechanical vibration intensity, resulting in decreased dipole oscillation quality and potentially compromising the overall inactivation performance.[6] Despite these environmental influences, non-thermal MW technologies exhibit a significant advantage in maintaining their effectiveness against emerging viral mutants.[6] This resilience stems from the fact that vibrational signatures are governed by the intrinsic physical properties of the virion – such as size and elasticity – rather than its genetic material and antigenic characteristics.[6] As a result, resonance behavior remains consistent even in the presence of escape mutations, ensuring sustained inactivation efficacy across evolving viral strains. Notably, the mechanisms underlying non-thermal MW inactivation also have significant implications in terms of safety. Accordingly, human cells resonate at much lower frequencies (approximately 100 MHz) compared to viral particles, creating a frequency mismatch that protects human tissues during non-thermal MW exposure (Fig. 2).[6]. Furthermore, this technology operates at a MW power density significantly below the non-thermal public safety limit of 100 W/m^2 averaged over 4 cm^2 for the 6–300 GHz range,[6,13] as established by the International Commission on Non-ionizing Radiation Protection (ICNIRP).[14] Taken together, these characteristics position non-thermal MW technologies as a biologically safe and highly targeted approach for airborne viral inactivation, potentially adaptable to a wide range of environmental conditions and pathogen types.

Table 1
Search strategy.

Criterion	Specification
Date of search	March 7, 2025
Databases searched	PubMed, Scopus, Google Scholar, ScienceDirect
Search terms	("microwave" OR "microwave irradiation") OR ("resonant energy transfer" OR "SRET") AND ("airborne virus" OR "respiratory virus" OR "virus")
Timeframe	From January 1, 2015, to February 28, 2025
Inclusion criteria	Experimental studies and reviews focusing on the antiviral effects of microwave irradiation on airborne respiratory viruses
Exclusion criteria	Articles not specifically addressing airborne viruses, aerosols, or microwave-based technologies; non-English full-text articles

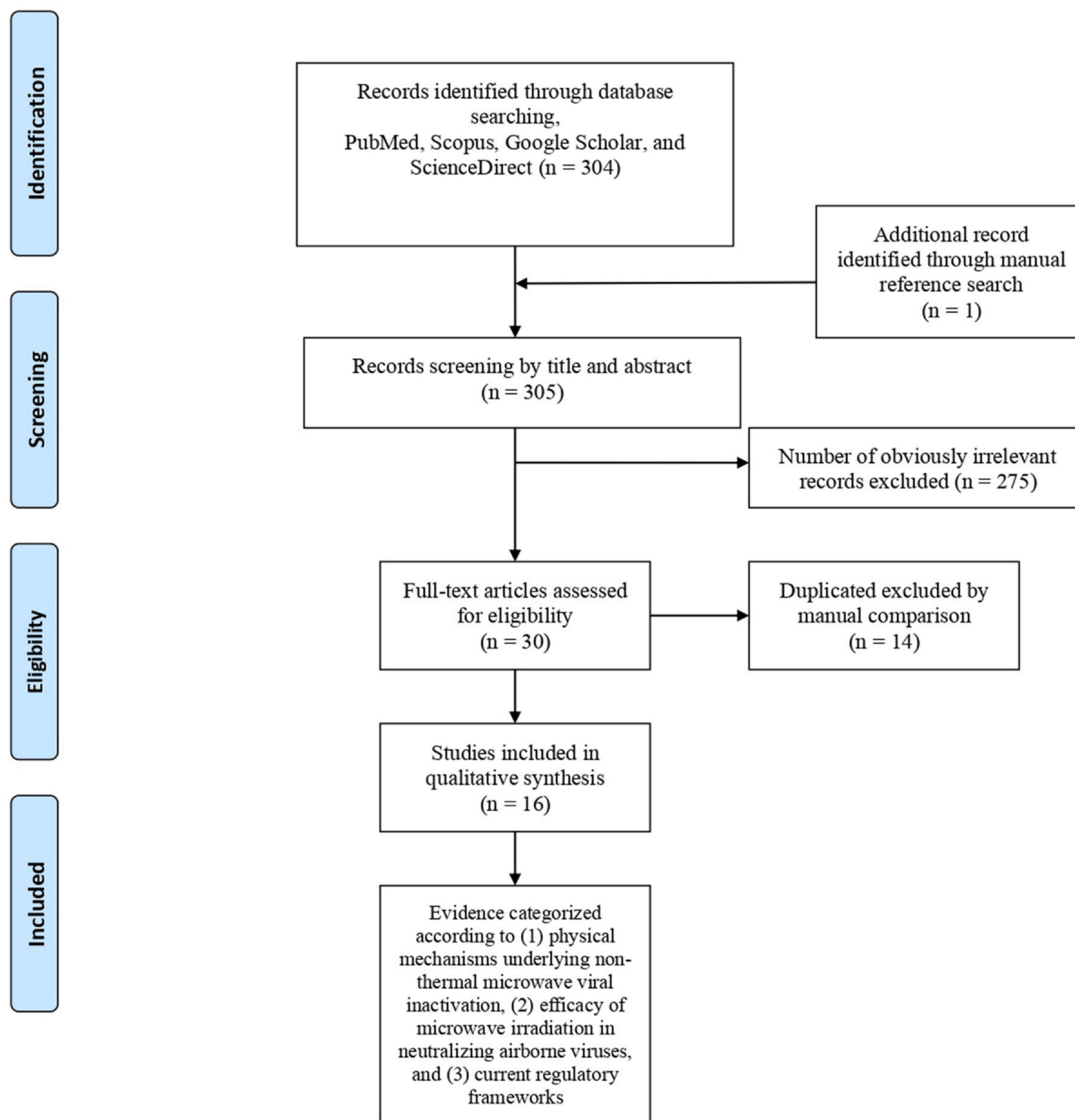

Fig. 1. Flow diagram of studies' screening and selection.

Efficacy of MW irradiation in neutralizing airborne viruses

The selective mechanism of non-thermal MW irradiation offers distinct advantages for airborne viral inactivation. Unlike aqueous environments, where rapid dielectric absorption by water molecules dominates energy dissipation, the low permittivity of aerosols facilitates preferential coupling of MW energy to viral components.[15] Historically, MW applications have evolved from using high, unsafe power densities against model viruses to safer, low-power exposures that may selectively inactivate human airborne pathogens by exploiting their vibrational frequencies. Wu and Yao demonstrated the efficacy of MW irradiation against aerosolized MS2 coliphage – a widely used surrogate for human respiratory viruses.[16] The experimental data demonstrated that MW exposure at 700 W for < 2 min induced 90% viral inactivation. In contrast, power outputs of 385 W and 119 W exhibited markedly reduced efficacy, with inactivation rates declining by 35% and 50%, respectively, relative to the 700 W benchmark. Notably, the inactivation effect exhibited a highly linear relationship with exposure time, primarily driven by structural damage to the viral surface and RNA. However, this investigation was constrained by its use of high-power densities, which were nearly 100-fold higher above the recommended safety threshold – making this approach unsuitable for directly irradiating room air in the presence of occupants.[16] In a notable technological advance, Hoff et al.[17] developed and tested three apparatuses for controlled MW exposure of aerosolized pathogens at four frequencies (7.5, 5.6, 4.0, and 2.8 GHz). The devices employed single-mode waveguides to ensure precise radiofrequency electric field exposure while maintaining compact designs suitable for high-biosafety environments. Simulations showed electric field strengths of 597–1321 V/m and attenuation coefficients of 0.014–0.108 Np/m.[17] Notably, exposure of aerosol streams to radiofrequency fields at 5.6 GHz led to significant 74% decrease in the survival rate of bovine coronavirus (BCoV) – a surrogate for SARS-CoV-2.[18] Within this framework, Cantu et al.[11] investigated the efficacy of low-level radiofrequency irradiation (6–12 GHz) for BCoV inactivation, demonstrating that targeted RF exposure achieved up to 77% viral reduction under optimized frequency and power conditions.[11] Building on this foundation, Wang et al.[8] successfully identified resonant frequencies for two human coronaviruses (SARS-CoV-2 and HCoV-229E) using a coplanar

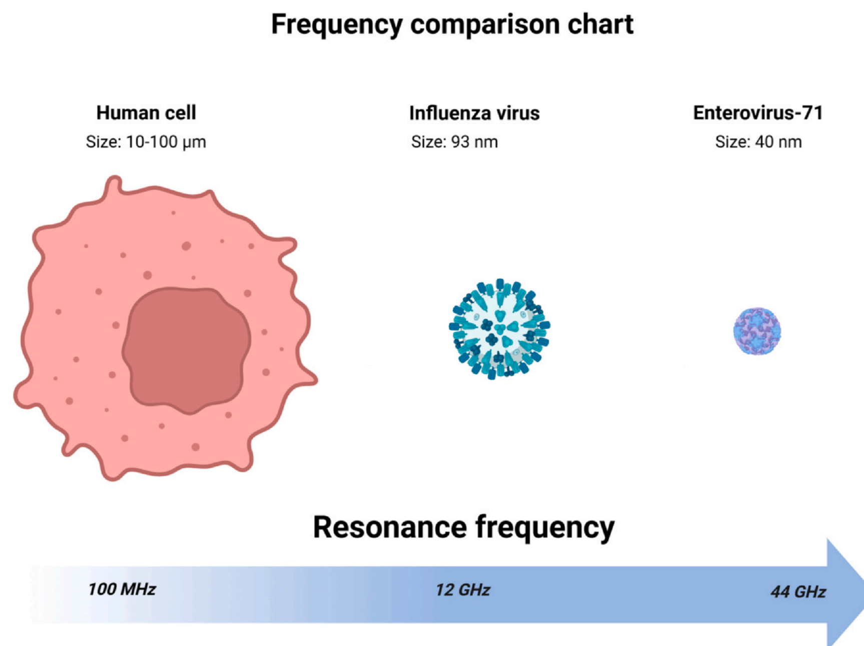

Fig. 2. Resonance frequency comparison chart for human cells and viral particles. The chart illustrates the relationship between particle size and resonance frequency for human cells, influenza virus, and enterovirus-71. Human cells (10–100 µm) resonate at approximately 100 MHz, while smaller viral particles resonate at significantly higher frequencies due to their reduced size and distinct biophysical properties. Influenza virus (93 nm) exhibits a resonance frequency near 12 GHz, whereas enterovirus-71 (40 nm) resonates around 44 GHz. This frequency mismatch underscores the selectivity of non-thermal microwave (MW) technologies, which target viral particles without affecting human cells. The ability to exploit these differences in resonance frequencies ensures both efficacy in viral inactivation and safety for human tissues during MW exposure (*Created with Biorender.com*).

waveguide sensor. Their findings revealed that SARS-CoV-2 exhibited structural resonance at 4 GHz and 7.5 GHz, with maximum MW absorption efficiency reaching 32% at 4 GHz for a viral titer of 10^7 plaque forming units/mL. In the authors' experimental setup, the observed resonant frequencies were determined to be unaffected by variations in virus concentration or the pH of the medium.[8] More recently, Manna et al.[12] demonstrated that radiated MW irradiation effectively inactivated aerosolized SARS-CoV-2 within safe power limits. Specifically, a 90% reduction in viral infectivity was achieved under optimized conditions (8–10 GHz frequency range, 6 V/m field strength, 1-min exposure). The SRET mechanism was identified as the primary driver of viral disruption.[12] Extending their research to influenza virus H1N1 and specific SARS-CoV-2 variants (delta and omicron), the same research group observed infectivity reductions of 80–90% for all tested SARS-CoV-2 strains under similar conditions.[19] However, influenza viruses required higher frequencies (up to 16 GHz) and longer exposure times (5 min) to achieve comparable results, highlighting the need for virus-specific parameter optimization.[19] In a separate study, Bia et al.[20] examined MW irradiation for aerosolized avian influenza A(H5N1) virus inactivation. The authors identified an optimal frequency range of 11–13 GHz, achieving an average viral titer reduction of 89% after a 10-min exposure, with peak efficacy observed within the 11–12 GHz range. Their findings also confirmed a time-dependent effect, as shorter exposures resulted in progressively lower inactivation rates.[20] Collectively, these studies support the usefulness of MW irradiation as a tool for the non-thermal inactivation of clinically significant respiratory viruses dispersed in aerosols (Table 2), presenting scalable approaches to reduce airborne transmission risks among diverse pathogens while maintaining safety thresholds compatible with human and animal exposure guidelines. Importantly, they also underscore the need to optimize MW parameters – including frequency and exposure duration – to each virus's unique structural properties to maximize efficacy.[12,19,20] Consequently, MW-based IPC devices intended for deployment in healthcare, community, or veterinary settings should be designed to emit specifically selected frequency ranges tailored to the varying susceptibilities of different viruses, thereby ensuring broad-spectrum efficacy and adaptability across diverse environments.

Current regulatory frameworks governing the deployment of non-thermal MW devices for airborne virus inactivation

Building on the expanding evidence base, non-thermal MW irradiation has gained recognition from regulatory bodies as a method for mitigating airborne respiratory virus transmission, subject to specific safety and efficacy frameworks.[21] In terms of safety, the EU mandates compliance with Directive 2014/30/EU for electromagnetic compatibility,[22] while the USA regulations requires adherence to Occupational Safety and Health Administration general industry standards (29 CFR 1910)[23] and the Federal Communications Commission (FCC) guidelines – including OET Bulletin No. 65 (August 1997).[24] In line with other radiofrequency-emitting devices, EU regulations set a specific absorption rate limit of 2.0 W/kg averaged over 10 g of tissue under Council Recommendation 1999/519/EC,[25] whereas the FCC enforces a limit of 1.6 W/kg averaged over 1 g of tissue.[24] From an efficacy perspective, manufacturers of MW-based systems for airborne virus inactivation are required to validate their effectiveness through standardized testing procedures.[21] Notably, the European Commission's 2024 report *Suppressing Indoor Pathogen Transmission* acknowledged MW radiation as a novel decontamination method capable of inactivating airborne viral pathogens.[21] In addition, the technical specifications outlined in the document indicate that MW systems can create localized protection zones extending up to 3 m for individual use, as well as secure areas of approximately 50 square meters for room-scale applications.[21] These collective advancements establish MW technology as a versatile and promising solution for bolstering both human and veterinary public health measures against airborne viral pathogens across diverse environments.

Table 2
Summary of studies investigating the inactivation of viral aerosols using microwave irradiation.

Study	Objective	Methods	Key Results	Conclusions
Wu & Yao (2014)[16]	Investigate inactivation of MS2 coliphage aerosols by microwave irradiation.	MS2 viruses aerosolized and exposed to microwaves (700 W, 385 W, 119 W) for ~2 min.	90% inactivation at 700 W; linear relationship between exposure time and inactivation rate. Scanning electron microscopy revealed surface rupture and RNA damage.	Direct microwave irradiation is effective for rapid viral aerosol inactivation, with potential applications in air sanitization.
Manna et al. (2023)[12]	Assess SARS-CoV-2 inactivation in aerosol using microwaves under safe power levels.	SARS-CoV-2 aerosols exposed to 8–10 GHz microwaves at ≤6 V/m. Viral titer reduction measured via cytopathic effect on Vero E6 cells.	Achieved > 90% reduction in infectivity within 1 min under optimized conditions (frequency step: 20 MHz; dwell time: 0.05 s).	Microwaves can safely and effectively reduce SARS-CoV-2 infectivity, with potential for indoor air sanitization applications.
Hoff et al. (2022)[18]	Investigate bovine coronavirus bioaerosol inactivation under pulsed radiofrequency electromagnetic exposure.	Bovine coronavirus aerosols exposed to ~5.6 GHz RF waves for up to 0.85 s at ~41.9 kV/m electric field amplitude under laminar flow conditions.	Reduced survival rate by ~74%; increased variance and standard deviation of results compared to controls due to combined thermal and non-thermal effects.	Pulsed radiofrequency exposure demonstrates feasibility for bioaerosol sanitization.
Manna et al. (2023)[19]	Investigate the efficacy of radiofrequency microwaves on SARS-CoV-2 variants (delta, omicron) and H1N1 influenza virus.	Aerosols exposed to optimized radiofrequency conditions (8–10 GHz for SARS-CoV-2; 8–16 GHz for H1N1). Viral titers measured post-exposure.	SARS-CoV-2 variants showed consistent 80–90% reduction; H1N1 required higher frequencies (up to 16 GHz) and longer exposure times (5 min).	Microwaves effectively inactivate diverse respiratory viruses, though optimal parameters vary by virus type.
Bia et al. (2025)[20]	Evaluate microwave efficacy against aerosolized avian influenza A(H5N1).	A(H5N1) aerosols exposed to 8–16 GHz microwaves for varying durations (1–10 min).	Optimal frequency band: 11–13 GHz; achieved up to 94% reduction with 5-minute exposure. Shorter durations yielded lower efficacy.	Microwave treatment is a promising non-chemical strategy for mitigating avian influenza transmission risks in high-risk environments.

Discussion

Non-thermal MW irradiation: current opportunities and applications

Over the past three decades, the world has confronted three major pandemics caused by respiratory viruses – the 2003 SARS-CoV-1 epidemic,[26] the 2009 A(H1N1) swine-origin influenza outbreak,[27] and the recent COVID-19 crisis.[28] Each of these pandemics has been significantly influenced by airborne transmission, highlighting its critical role in the spread of respiratory diseases.[29,30] More recently, the avian influenza A(H5N1) virus has garnered attention as a potential candidate for triggering another pandemic, emphasizing the critical necessity for robust preparedness and mitigation strategies.[31,32] While vaccination remains a cornerstone in preventing viral respiratory infections, its effectiveness is compromised by several challenges, including limited availability, growing vaccine hesitancy,[33] declining public trust, inequitable global distribution,[34] and the rapid emergence of escape variants,[35] underscoring the urgent need for further innovative IPC strategies.[36] This necessity is further amplified by the challenges associated with traditional disinfection methods – including chemical agents, ultraviolet C (UVC) radiation, and ozone – which are hindered by issues such as limited penetration efficacy, potential safety concerns, and adverse environmental impacts.[37,38] Among the physical strategies currently available for virus inactivation,[39] non-thermal MW irradiation has emerged as a scalable and adaptable method for mitigating the airborne transmission of clinically significant respiratory viruses, including SARS-CoV-2, influenza virus H1N1, and avian influenza A (H5N1). The reviewed evidence highlights the safety and efficacy of this approach, and when combined with stringent regulatory frameworks governing non-thermal MW-emitting devices, it paves the way for diverse real-world applications in both fixed and portable settings. In diverse healthcare environments – including hospitals, outpatient clinics, and medical transportation services[40] – MW devices offer promising potential as a valuable adjunct to existing IPC measures. By enabling continuous viral inactivation in high-risk settings where exposure to airborne pathogens is both frequent and potentially severe, this approach could significantly enhance safety for both patients and healthcare professionals. Notably, the potential integration of MW systems into existing frameworks underscores the importance of developing comprehensive strategies that combine various non-pharmaceutical interventions (NPIs) to create more effective and layered protection against respiratory pathogens. Crowded indoor environments represent another critical domain for deploying MW irradiation technology, particularly during seasonal outbreaks of respiratory viruses.[41] Integrating MW irradiation systems into existing indoor air quality infrastructures or deploying portable devices could substantially mitigate viral transmission risks in various settings, including occupational, educational, commercial, and travel environments. We believe that this approach would be particularly beneficial in situations where adherence to traditional preventive measures, such as mask-wearing, is inconsistent and/or impractical.[42] In zootechnical environments such as poultry farms, MW-based systems could be seamlessly integrated into ventilation systems to reduce zoonotic spillover risks associated with pathogens like avian influenza A(H5N1).[43,44] Given the demonstrated susceptibility of enveloped viruses to non-thermal MW irradiation, future research should prioritize its potential to inactivate other significant airborne pathogens – including Morbillivirus, the causative agent of measles; respiratory syncytial virus (RSV) a leading cause of bronchiolitis and pneumonia in infants and the elderly;[45,46] parainfluenza virus, which causes respiratory illnesses ranging from mild infections to severe conditions such as croup and pneumonia;[47,48] and human metapneumovirus, responsible for upper and lower respiratory tract infections – including bronchiolitis and pneumonia –

especially in children and immunocompromised individuals.[49,50] Although experimental data for these viruses need confirmation, the principles of SRET suggest that MW irradiation could be tailored to target their distinct structural and biophysical characteristics. Furthermore, both for viruses where MW irradiation has already shown efficacy and in future trials involving other pathogens, it is critical to deepen our understanding of the factors influencing inactivation efficiency. Key variables such as virus concentration, specific emission frequency, irradiation duration, air humidity, temperature, air composition, and emitter design warrant systematic investigation. Additionally, addressing challenges posed by shielding effects from metallic surfaces[21] should be a focus of future research to optimize the practical application of this technology.

Installation, maintenance, and cost considerations

The effective implementation of non-thermal MW irradiation technology for IPC fundamentally depends on a comprehensive understanding of installation, maintenance, and cost factors – all considerations that are especially crucial in resource-limited environments where feasibility and scalability are paramount.[51] MW systems are designed for operational flexibility, enabling seamless integration into existing heating, ventilation, and air conditioning infrastructures for continuous air disinfection in large spaces, as well as deployment as standalone portable units for targeted applications.[21] Installation procedures are notably straightforward, requiring only standard electrical work rather than specialized technical expertise, which significantly reduces implementation barriers in diverse indoor settings. In addition, the modular designs can accommodate both wall-mounted fixed installations and mobile configurations, allowing for repositioning across different spaces as operational needs evolve. This adaptability makes MW irradiation technology especially well-suited for high-risk environments, including emergency departments, infectious disease and intensive care units, endoscopy and dental wards, outpatient clinics, as well as veterinary and zootechnical facilities. Importantly, maintenance requirements for MW devices are minimal, as these systems operate continuously once installed without requiring routine servicing. Remote monitoring and control capabilities through dedicated software platforms enable real-time system oversight and parameter adjustment without on-site intervention. Furthermore, installed devices can be remotely updated with new resonance frequencies as research identifies additional pathogen targets, ensuring continued efficacy without hardware replacement. Importantly, the absence of consumable components eliminates both recurring replacement costs and associated waste disposal considerations, while the chemical-free operation removes concerns regarding hazardous substance handling and environmental impact.[51] Commercially available MW systems also demonstrate notably limited power consumption, typically operating at 8–9 watts, which is substantially lower than comparable air disinfection technologies. As a result, relative to other advanced air decontamination technologies,[52,53] MW systems can exhibit a more advantageous cost-benefit ratio, particularly considering their adaptability, energy efficiency, and inherent durability. Collectively, these characteristics substantiate the practical and effective integration of MW irradiation technology across a diverse spectrum of real-world settings.

Limitations and future research directions

A significant limitation in the current understanding of non-thermal MW irradiation's antiviral efficacy is that all reviewed studies have thus far been conducted under controlled laboratory conditions (Table 2). This constraint, however, is not unique to MW technology, as it similarly affects other established sanitation methods, including UVC irradiation. To bridge this gap and facilitate the translation of MW technology into clinical practice, future research must prioritize clinical validation studies that specifically target airborne viral pathogens. A promising approach would involve employing a Coriolis Micro air sampler with sequential sampling at defined intervals (baseline through 24 h post-MW activation), which could provide a robust framework for quantifying airborne viral load reduction in real-world settings.[53] Such a protocol would generate essential clinical evidence on the efficacy of MW irradiation in reducing airborne viral loads, thereby complementing existing laboratory findings and supporting the integration of this technology into routine IPC strategies. Beyond direct viral inactivation, it is important to consider that real-world applications of MW irradiation may theoretically exert selective pressures on indoor microbial communities, potentially altering their ecological dynamics.[54] Exposure to MW – via both thermal and non-thermal effects – could favor an increased relative abundance of bacterial genera inherently resistant to MW exposure, elevated temperatures, and desiccation.[54] Consequently, these resilient genera may become more prevalent in environments where MW technology is routinely employed. While non-thermal MW exposure may also inactivate various bacterial species,[55] we currently lack direct evidence that the frequency ranges effective against airborne viruses exert similar antibacterial effects. In this context, the impact of non-thermal MW exposure on the composition of indoor microbiota – and the subsequent implications for respiratory and cardiovascular function in otherwise healthy individuals[56] routinely exposed to MW-emitting devices – remains an open area for future research. Parallel evaluation of health indicators and profiling of the indoor microbiota will be crucial to detect potential shifts in community composition. Pursuing this research direction will be essential not only to clarify the potential indirect effects of MW technology on microbial populations but also to confirm its safety profile, particularly with respect to long-term exposure. Another important area requiring further investigation is how environmental factors – such as temperature and pH – may influence the efficacy of non-thermal MW irradiation in virus inactivation. In this regard, Xiao et al.[57] have previously shown that 2.8 GHz MW irradiation inactivates MHV-A59 (a surrogate for human coronaviruses) more effectively at higher temperatures compared to room temperature. These observations suggest that thermal conditions may modulate the resonance or structural susceptibility of viral particles to MW energy. In this regard, the influence of environmental temperature on virus inactivation by electromagnetic waves might be attributed to variations in frequencies and power densities, as well as inherent differences in viral biophysical properties.[6] Similarly, it remains to be determined whether the chemical environment surrounding aerosolized viruses – which influences aerosol pH[58] – could alter resonance frequencies or impact the efficiency of MW resonant absorption. We also acknowledge that elevated volatile organic compounds (VOCs) loads in specific indoor environments (e.g., poultry houses where ammonia levels can average 23 ppm)[59] may introduce additional complexity to the efficacy of non-thermal MW irradiation for airborne virus inactivation. However, while VOCs are recognized to interact with MW energy,[60] there remains limited direct evidence elucidating their specific impact on virus inactivation mechanisms. Finally, to contextualize the potential applications of non-thermal MW irradiation for air decontamination, it is crucial to discuss its position relative to recent alternative approaches like advanced photohydrolysis technology (APHT). While MW irradiation can achieve substantial inactivation rates by targeting viral structural integrity through vibrational resonance,[6] APHT utilizes photochemical reactions to generate reactive oxygen species (ROS), including hydroxyl radicals, resulting in near-complete inactivation (> 99%) across a broad spectrum of pathogens under optimal conditions.[61] Accordingly, Peel et al.[52] have recently reported high inactivation efficacy against aerosolized SARS-CoV-2 and RSV. However, the two

approaches differ significantly in their mechanisms and potential drawbacks. Accordingly, the MW technology operates within the GHz range, employing frequency mismatch to ensure safety for human tissue[6] and adhering to strict regulatory standards for electromagnetic compatibility and specific absorption rates.[21] In contrast, APHT functions by dispersing ROS, which raises concerns about potential cumulative oxidative stress from inhalation in indoor environments, particularly for individuals with chronic lung conditions, as well as possible interactions with environmental free radicals.[62] In addition, APHT's performance may be affected by the heterogeneous distribution of ROS due to air currents and room geometry, potentially creating "cold spots" characterized by suboptimal inactivation.[62]

Concluding remarks

Notwithstanding the current limitations, non-thermal MW irradiation holds transformative potential as an innovative physical intervention for inactivating airborne respiratory viruses – a paradigm shift that could drive lasting advancements in IPC. Notably, this technology uniquely targets viral structural integrity via CAV, while ensuring human tissue safety through frequency mismatch – utilizing frequencies in the GHz range for viral resonance, distinct from the 100 MHz frequency associated with human cells. This precision and safety profile position MW technology as a biologically targeted and secure solution. The demonstrated broad-spectrum applicability spans enveloped viruses of critical public health concern, including pandemic-potential pathogens like avian influenza A(H5N1), as well as seasonal threats. Regulatory preparedness is demonstrated through adherence to critical international safety standards, complemented by stringent efficacy protocols that mandate the documentation of logarithmic viral load reduction. Practical implementations could integrate MW systems into heating, ventilation, and air conditioning infrastructures for continuous air disinfection in healthcare settings and high-risk zoonotic environments such as poultry farms, while portable devices could assure personal protection zones in at risk indoor environments. As a complement to vaccination campaigns and NPIs, this technology may effectively address critical limitations of biological countermeasures – particularly in combating antigenically drifted strains – while avoiding the safety and environmental constraints of ultraviolet irradiation and chemical disinfectants. Future directions should prioritize expanding the efficacy spectrum to include other common enveloped respiratory airborne viruses and addressing potential interference factors such as air humidity and metallic shielding effects. With these advancements, non-thermal MW-based inactivation could become a cornerstone of pandemic preparedness, providing a scalable, adaptive defense against both current and future airborne viral threats.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Silvio Brusaferro, Alberto Sangiovanni-Vincentelli, and Gaetano P. Privitera hold positions as consultants and members of the scientific advisory board for e4life Srl (Rome, Italy) – a company that develops devices for virus inactivation utilizing microwave irradiation technology. Luca Arnoldo is serving as the Principal Investigator for an ongoing clinical study assessing the efficacy of e4life Srl devices in nursing home environments. Laura Brunelli and Guglielmo Arzilli have no conflicts of interest to declare that are relevant to the content of this article.

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