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REVIEW

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Exposure at the indoor water–air interface: Fill water constituents and the consequent air emissions from ultrasonic humidifiers: A systematic review

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Abstract

This systematic review investigates the emissions from ultrasonic humidifiers (e.g., cool mist humidifiers) within indoor air environments, namely soluble and insoluble metals and minerals as well as microorganisms and one organic chemical biocide. Relationships between ultrasonic humidifier fill water quality and the emissions in indoor air are studied, and associated potential adverse health outcomes are discussed. Literature from January 1, 1980, to February 1, 2022, was searched from online databases of PubMed, Web of Science, and Scopus to produce 27 articles. The results revealed clear positive proportional relationships of the concentration of microorganisms and soluble metals/minerals between fill water qualities and emitted airborne particles, for both microbial ($n = 9$) and inorganic ($n = 15$) constituents. When evaluating emissions and the consequent health outcomes, ventilation rates of specific exposure scenarios affect the concentrations of emitted particles. Thus, well-ventilated rooms may alleviate inhalation risks when the fill water in ultrasonic humidifiers contains microorganisms and soluble metals/minerals. Case reports ($n = 3$) possibly due to the inhalation of particles from ultrasonic humidifier include hypersensitivity pneumonitis in adults and a 6-month infant; the young infant exhibited nonreversible mild obstructive ventilator defect. In summary, related literature indicated correlation between fill water quality of ultrasonic humidifier and emitted particles in air quality, and inhalation of the emitted particles may cause undesirable health outcomes of impaired respiratory functions in adults and children.

KEYWORDS
environmental health, indoor air quality, inhalation risk, risk assessment, ultrasonic humidifier, water quality

1 | INTRODUCTION

Portable ultrasonic humidifiers with 1.6 MHz ultrasonic nebulizers are commonly used consumer products to emit fine water droplets to increase indoor air humidity,[1,2] and can relieve dryness in the skin, nose, and eyes through fine water droplets. Unlike warm steam humidifiers (also called vaporizers or evaporative humidifiers), which emit pure water steam through heating the water to boiling, the fine water droplets generated by ultrasonic humidifiers (also called cool mist humidifiers) contain aqueous constituents.[3] Once in the room air, water evaporates to form airborne particulate matter (PM) from the dissolved aqueous constituents. Children and adults inhale the PM while using an ultrasonic humidifier. PM is defined as solid particles and/or liquid droplets suspended in air, and can be composed of various chemicals released or formed from a wide range of sources, such as anthropogenic activities. The diameter of PM has a wide range from submicron to tens of microns and can cause adverse health effects when inhaled. In ambient air, the primary USEPA regulated $PM_{2.5}$ (aerodynamic diameter <2.5 μm) standard is an annual average of <12.0 μg/m^3 and a 24-hour standard of ≤35 μg/m^3.[4] Therefore, a review of the relationships between water quality and consequent air quality is a valuable and previously overlooked investigation for assessing human exposure at the indoor water–air interface.

Natural and tap waters contain inorganic dissolved minerals that are collectively measured as total dissolved solids (TDS), which includes dissolved cations and anions. In tap water, Ca, K, Mg, and Na are typical metal cations whose aqueous concentrations vary in a wide range from about one thousand to tens of thousands of μg/L.[5,6] Other trace metals occur in tap water at much lower concentrations from one to about a thousand μg/L.[7] These include toxic metals known to adversely affect human health via ingestion that are regulated by the United States Environmental Protection Agency (USEPA) National Primary Drinking Water Standards (e.g., As, Cd, Cr, Cu, and Pb).[8] In addition, USEPA sets guidelines, but not regulations, for Secondary Maximum Contaminant Levels for select inorganic metals (i.e., Al, Fe, Mn, Ag, and Zn) to prevent corrosion, aesthetic effects, and taste and odor issues.[8] For Mn, the drinking water concentration is regulated as a maximum acceptable concentration of 120 μg/L in Canada for its ingestion health risks.[9] In ambient air, the concentrations of metals are usually low, except for locations near industrial emissions and heavy traffic roads.[10,11] Among the six criteria air pollutants, Pb is the only regulated metal in the USEPA National Ambient Air Quality Standards, at the level of 0.15 μg/m^3 for a rolling 3-month average.[4] Inhaled inorganic metals bound in PM, when deposited in the lung, can transport to blood and thus pose toxicity to exposed populations.[12–15] Previous studies have shown that there were positive relationships between the waterborne metals and emitted airborne metals from ultrasonic humidifiers; more dissolved metals in the fill water become more metals emitted in airborne PM.[16–19]

In addition to metals, microorganisms can also occur in tap water and/or fill water of the ultrasonic humidifier.[20–22] Microbial growth in the ultrasonic humidifier reservoir is a possible human health concern since it is acknowledged that growth of microorganisms happens when the humidifier is not cleaned between uses. Lee et al.[23] filled an ultrasonic humidifier with local tap water, operated the humidifier for 15 days, and collected bioaerosols of bacteria and fungi; results showed that the colony forming unit (cfu) in air increased from 6979 cfu/m^3 on the sixth day to 46 431 cfu/m^3 on the ninth day.

The ventilation rate in indoor environments also plays an essential role in the concentrations of emitted waterborne constituents that build up within the indoor air,[24] including metals and microorganisms. Greater ventilation rates increase the air exchange of indoor air with ambient air, and therefore, indoor airborne PMs are cleared at a faster rate, reducing the contamination indoors. Increased ventilation of homes is acknowledged to minimize health risks from indoor pollutants.[25] A study summarized epidemiologic studies and reported significant increased relative risks of respiratory disease and sick building syndrome symptoms associated with reduced ventilation rates.[26] Sundell et al.[27] indicated that ventilation rates of >0.5 h^{-1} were associated with reduced health risks of allergic manifestations in children in residential settings.

This review aims to comprehensively evaluate the data of fill water quality and indoor air quality for chemicals and microorganisms emitted from ultrasonic humidifiers. A human health risk assessment requires a comprehensive understanding of all relevant exposure parameters.

As indicated by the PROSPERO database, there is no review project on ultrasonic humidifier fill water and its contributions to particulate matter and contaminants in indoor air. The objectives of this systematic review are as follows: (i) summarize prior publications on characteristics of humidifier fill water quality and the consequent airborne particles emitted from ultrasonic humidifiers; (ii) investigate potential correlations between fill water quality and indoor air quality induced by the emissions of particles and microbial species from ultrasonic humidifiers.

Practical Implications

- Ultrasonic humidifiers, which are a commonly used consumer product to increase indoor air moisture, emit submicron, respirable particles containing inorganic chemicals, metals, organic chemicals, particles, fibers, and microorganisms present in the fill water.
- For dissolved chemicals (inorganic chemicals, metals, and an organic chemical biocide), the concentrations emitted to indoor air are proportional to the concentrations in the fill water.
- Adverse human health outcomes from a few case reports indicate that lung injury risk occurs, even though the incidence of hospitalized patients is low.
- Consumer guidance on use and implications of ultrasonic humidifiers, also called cool mist humidifiers, is sparse and could be improved.

2 | METHODS

2.1 | Search strategy

Databases include Web of Science Core Collection from Clarivate Analytics, PubMed from National Library of Medicine (NLM), and Scopus. Only research articles were included as document type;

conference papers, letters, reviews, and book chapters were excluded. The search terms are "(TI=(ultrasonic humidifier)) OR AB=(ultrasonic humidifier)" for Web of Science Core Collection, "ultrasonic humidifier[Title/Abstract]", with date filters from 1980/1/1–2022/2/1, for PubMed, and "TITLE-ABS ("ultrasonic humidifier") AND PUBYEAR > 1980 AND (LIMIT-TO (DOCTYPE, "ar"))" for Scopus. The range of publication dates was set as 01/01/1980 to 02/01/2022, as the ultrasonic humidifier was invented approximately in 1980.

2.2 | Inclusion/Exclusion criteria

The screening criteria followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) method.[28,29] Primary screening was purposefully broad. Papers were more rigorously screened in the second round by two independent reviewers. Differences between reviewers' findings, that could not be reconciled initially, were brought to a third reviewer for a final decision. Articles in the second round were required to have original, experimental data, and to include the diameter or size distribution, mass concentration, number concentration of PM, and the experimental/exposure room information. Articles discussing non-steady-state emissions were excluded. Eligible research articles were included for full-text review in the next step.

2.3 | Data analysis

Based on data from the articles selected for this review, linear regressions were performed in R Studio[30] on the mass concentrations of waterborne contaminants and the mass concentrations of airborne, emitted contaminants for PM, organic compound of humidifier biocide, asbestos, soluble minerals and metals, and insoluble metal oxides. The *p*-value was obtained from linear regression models in R, and alpha value is 0.05 in this review. For the PM regression analysis, some studies include water quality data of TDS, while others include water quality data of fingerprint tap water minerals, Ca, Na, K, and Mg. In the review, parallel, compatible comparison of the emitted PM versus TDS or partial tap water minerals was conducted. The emitted PM were measurements from scanning mobility particle sizer (SMPS) or light scattering instruments, instead of conventional gravimetric methods. The upper size range discussed in this review was $PM_{2.5}$, as this parameter is typically reported in atmospheric and indoor air quality studies to assess human health risks. The particle size distributions of emitted PM were analyzed using Kolmogorov–Smirnoff (K-S) tests to compare statistical identical distributions measured by SMPS, when the TDS of various fill water were in the range of 27–1110 mg/L. Relationships between airborne particle diameter (expressed in count median diameter, the central tendency of a particle size distribution) and fill water quality of TDS were analyzed by linear regression.

3 | RESULTS

3.1 | Study characteristics

Of the 286 articles identified from Web of Science, PubMed, and Scopus databases, 133 duplicates were removed, and 153 records were screened in abstract and title for ultrasonic humidifier emissions and associated case reports. After exclusion of articles without access and without steady-state data, 27 articles were included in this review (Figure 1). In addition, Table S1 summarizes the characteristics of included literature, and the majority of ultrasonic humidifier studies focus on PM and some on microbial emissions.

For the assessment of water quality and resulting air quality, the articles were grouped into categories based on the whether the contaminant was soluble or insoluble, and chemical or microbial:

- Soluble aqueous constituents
- Insoluble inorganic constituents
- Microbial-related constituents

3.2 | Emissions of soluble aqueous constituents from ultrasonic humidifiers

3.2.1 | Mass concentrations of PM and its chemical composition

As seen in Figure 2, ultrasonic humidifiers aerosolize soluble minerals, metals, and a humidifier biocide [i.e., polyhexamethyleneguanidine (PHMG)], which was the only organic chemical revealed by the systematic review. There is strong correlation between soluble fill water constituents and emitted constituents (i.e., TDS, soluble metals, and organic biocide). The mechanism of ultrasonic humidification is to produce fine water droplets via an ultrasonic nebulizer, and the emitted water droplets contain soluble water constituents and also suspended insoluble particles in the fill water.[1] Emitted fine water droplets rapidly evaporate in the indoor air,[2,31] resulting in elevated levels of PM of inorganic and organic chemicals. The general trend for the mentioned contaminants is the greater mass concentration in the fill water, the greater mass emitted from the ultrasonic humidifiers.

Emitted PM represents particulate matter in different size bins smaller than 2.5 μm of the measurement instrumentation. The mass concentration and size distribution are measured by SMPS or light scattering instruments, and the measured size bins may be different. Figure 2A,B indicate that the emitted PM levels in an experimental room or chamber are strongly correlated to waterborne TDS and the major cations of Ca + Na + K + Mg in tap water as humidifier fill water, regardless of the room size and ventilation conditions. The metals Ca + Na + K + Mg were selected as Park et al. only reported these metals[32] and similar data were also available for references.[16–18] The *p*-values for the slopes of Figure 2A,B are significant ($p < 0.05$), validating the positive, linear relationships between water constituents

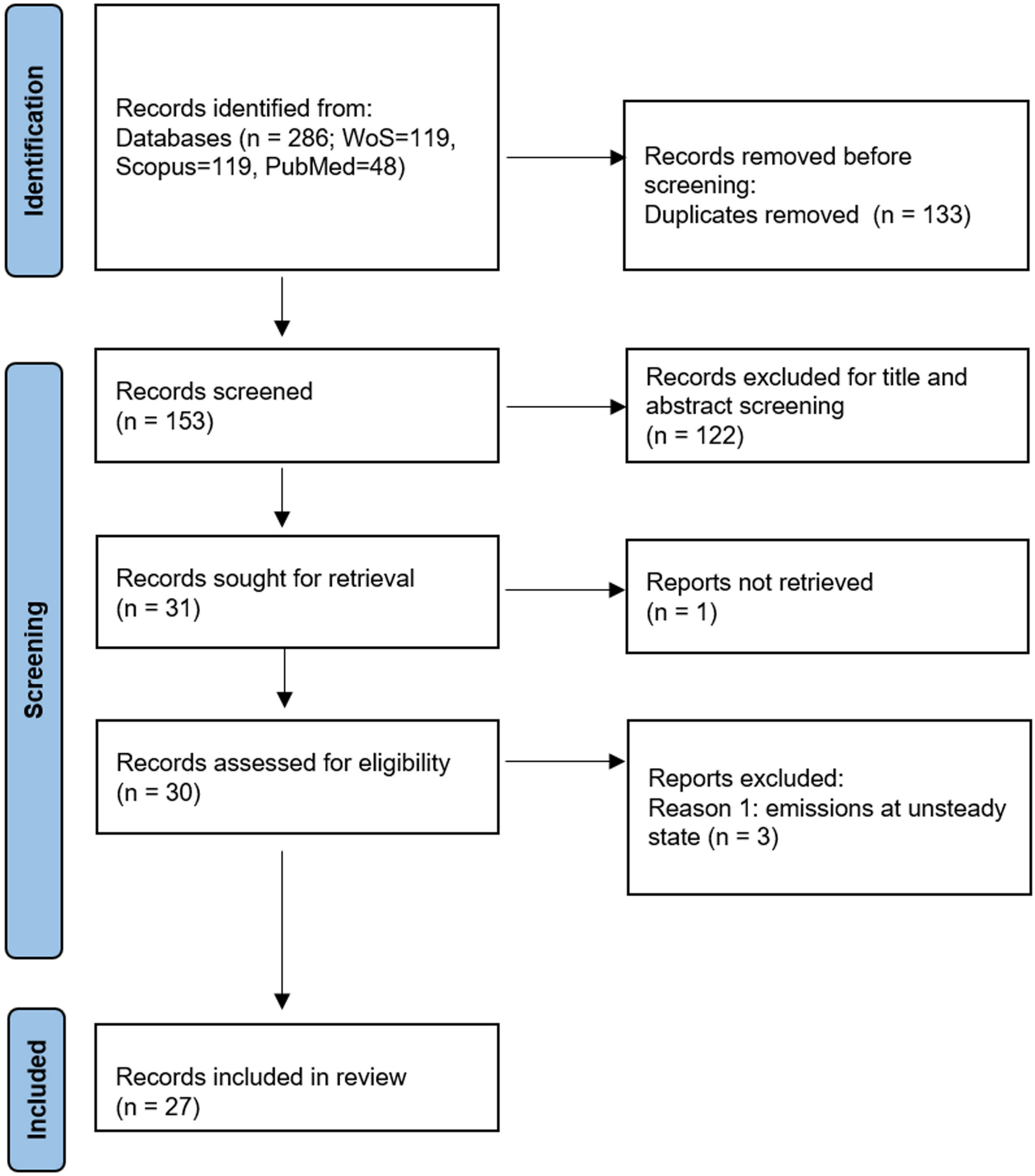

FIGURE 1 PRISMA flow diagram of literature search result

and airborne PM. The slope of 1.14, shown in Figure 2A, is in good agreement with prior literature.[16,18,33]

In addition, the linear regression analysis shows that the slope for humidifier biocide of PHMG is significant, ($p < 0.05$), indicating strong linear relationship between waterborne organic compound of PHMG and the emitted compound in room air (Figure 2C).

3.2.2 | Size distributions of PM

Table 1 indicates the count median diameters (CMD) and geometric standard deviations (GSD) of published particle size distributions from ultrasonic humidifiers as measured by SMPS. The covered TDS range is 11–1110 mg/L, and the emitted PM has CMD values of

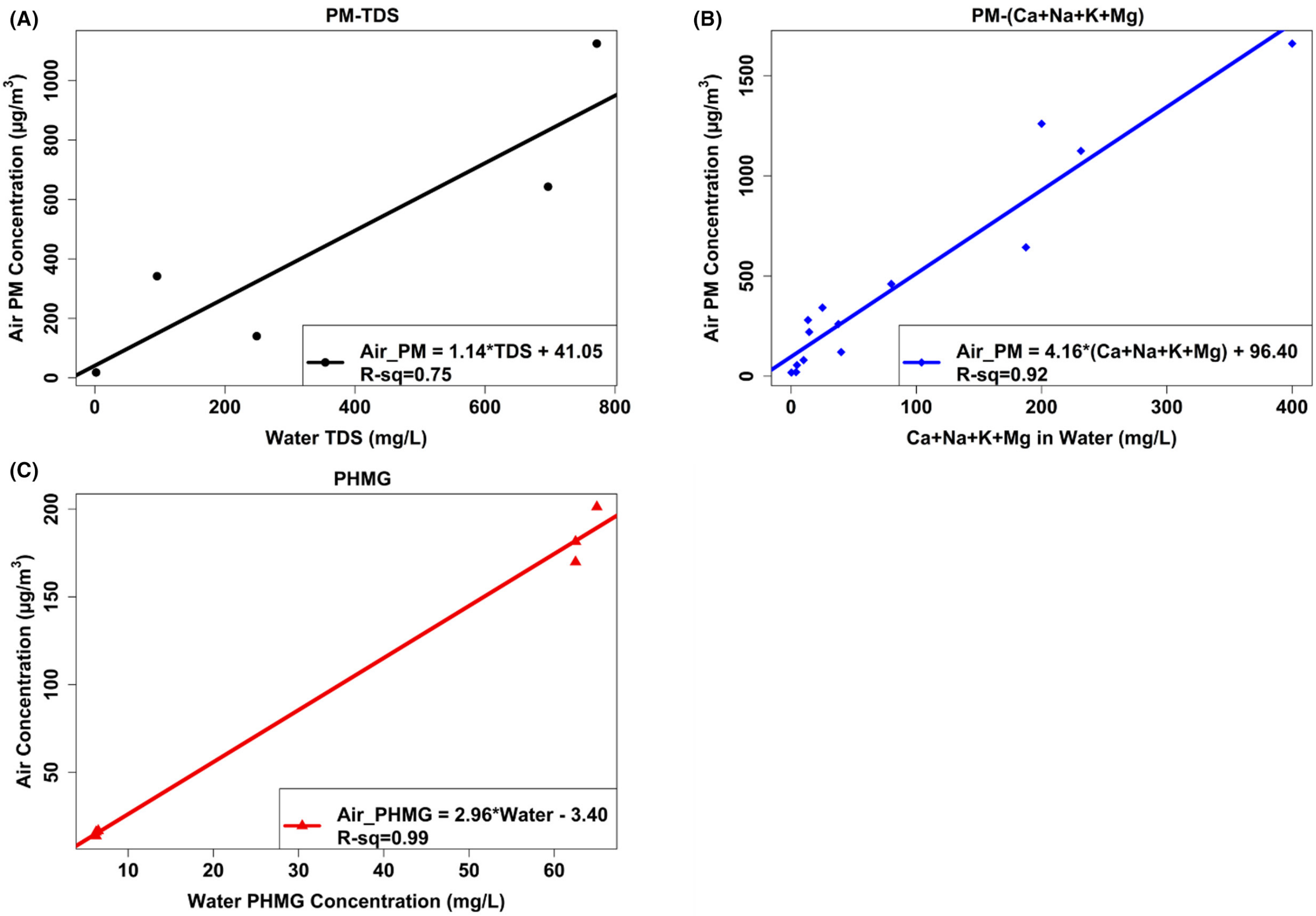

FIGURE 2 Linear regressions on the mass concentrations of airborne constituents from emissions of ultrasonic humidifier and mass concentrations of waterborne constituents. (A) Airborne PM versus aqueous TDS[17,18]; (B) PM versus (Ca + Na + K + Mg), partial mineral content in fill water[17,18,32]; (C) PHMG[34] (PHMG indicates polyhexamethyleneguanidine).

115–250 nm. The GSD values indicated polydispersity of particle size distributions from all included research articles. Figure 3 shows the size distributions of humidifier-generated PM by different ultrasonic humidifiers in different rooms. The SMPS instrument only measures particles up to 740 nm and lacks data for larger particles, such as PM_{10}. However, for the emitted PM, previous ultrasonic humidifier studies indicated that the majority were respirable $PM_{2.5}$,[16] and some further indicated that approximately 90% of the emitted particles were PM_1.[18,35] Umezawa et al. showed that the higher the TDS, the larger the peak diameter of the size distribution of produced PM in a realistic chamber.[36] The CMD of emitted particles and the peak diameter of the size distributions were in the range of 100–200 nm, when the fill water contained concentration of 6.5–65 mg/L PHMG or TDS <100 mg/L, indicated by Figure 3A,C,D. From Figure 3C,D, when the fill waters were of TDS > 100 mg/L, the size distribution shifted to the right, indicating larger particles were generated from ultrasonic humidifiers filled with high TDS waters. The results indicate that emitted, airborne particles from ultrasonic humidifiers are submicron particles, of the size to be inhaled and deposited in human respiratory tract. Besides, K-S tests showed that all the inorganic particle size distributions in Figures 3B–E were statistically different (p-values <0.05, data shown in Table S2), indicating large variability in the size distribution of emitted PM when the ultrasonic humidifier was filled with various TDS waters and operated in different room conditions. The linear regression of fill water TDS and the CMD of emitted particles is shown in Figure 4, the correlation is strong with R-sq of 0.78, indicating that fill water of higher TDS would generate larger particles.

3.3 | Emissions of solid-phase metal oxides particles and asbestos fibers from ultrasonic humidifiers

3.3.1 | Mass concentrations of solid-phase metal oxides and asbestos

From Figure 5A, the solid-phase, insoluble iron or aluminum oxide particles were emitted from ultrasonic humidifier, and increased with aqueous metal concentration. The metal oxides were captured in water vapor emitted from the humidifier and condensed. For the asbestos regression analysis (Figure 5B), the slope is not significant

TABLE 1 Count median diameter and geometric standard deviation of ultrasonic humidifier PM

Ref.	PM, size range, nm	TDS[a], mg/L	CMD[b], nm	GSD[c]
Lau et al., 2020[35]	PM15-670	221	166.65	1.41
Sain et al., 2018[17]	PM14-740	75	139.86	1.78
Sain et al., 2018[17]	PM14-740	440	167.27	2.07
Sain et al., 2018[17]	PM14-740	510	185.19	2.14
Yao et al., 2020[18]	PM14-740	96	130.84	1.72
Yao et al., 2020[18]	PM14-740	697	174.19	1.84
Yao et al., 2020[18]	PM14-740	772	192.04	1.86
Umezawa et al., 2013[36]	PM10-410	11.1	115.83	1.46
Umezawa et al., 2013[36]	PM10-410	27.75	128.91	1.43
Umezawa et al., 2013[36]	PM10-410	111	195.42	1.43
Umezawa et al., 2013[36]	PM10-410	222	244.79	1.42
Umezawa et al., 2013[36]	PM10-410	555	228.62	1.75
Umezawa et al., 2013[36]	PM10-410	1110	211.77	1.65

[a]TDS = total dissolved solids. References 17, 18, 35, and represent tap water containing various anions and cations. Reference 36 used $CaCl_2$ solutions as fill water.

[b]CMD = count mean diameter.

[c]GSD = geometric standard deviation.

($p > 0.05$). While these two articles represent limited data for emission of metal oxide particles and fibers, the R-sq values of the asbestos and metals oxides are similar to those of PM and PHMG analyses (Figure 2), indicating good predictive trends from water constituents to emitted, airborne chemicals (Figures 5A,B).

3.3.2 | Size of solid-phase metal oxides and asbestos

For the solid-phase, insoluble metal oxides, the emitted particles had a diameter range of 220–570 nm measured by dynamic light scattering.[1] Statistical analysis of ANOVA showed non-significant differences in emitted particles, regardless if iron or aluminum oxides were investigated.

For asbestos, incremental fiber concentrations were added in the humidifier fill water (Figure 5B); The asbestos fibers in humidifier fill water were of approximately 50–150 nm × 810–2640 nm (median widths × lengths, with ranges of 50–6700 nm and 250–22 300 nm, respectively). Results show the size of emitted asbestos fibers were independent of fill water concentration.[37] The emitted fibers were approximately 50 nm × 800–2080 nm (median width × lengths, with ranges of 300–2500 nm and 500–5600 nm, respectively), which suggested that the emitted asbestos fibers were homogeneous in size regardless of the size occurrence in the fill water. Research by Roccaro et al.[38] reported that ultrasonic humidifiers emitted 10–18 asbestos fibers per liter of water into indoor air. Although the sizes of the asbestos fibers were not measured, Roccaro et al.[38] found that only a fraction of the fibers in the fill water were emitted, which is similar to Hardy et al.[37] who reported 0.03%–4.7% of the asbestos fibers were emitted. Thus, when filled with insoluble particles, 1.6 MHz ultrasonic humidifiers emit a narrow range of particle sizes. This result is consistent with industrial research where ultrasonic energy is applied to emit a select narrow range of sizes from polydisperse particle solutions.[39,40]

3.4 | Microbial emissions from ultrasonic humidifiers

3.4.1 | Number concentration of emitted microorganisms and endotoxins

Tap water microbial contaminants are demonstrated to be present in humidifier fill water and biofilms[41] and modeling demonstrates that human exposure can occur.[42] Studied microbial-related emissions from ultrasonic humidifiers include bacteria (e.g., *Legionella, E. coli, and Mycobacterium*), fungi, and endotoxins.[22,23,43–45] Compared to evaporative humidifiers, ultrasonic humidifiers clearly emit more waterborne microbial constituents.[46] The 6-stage Andersen cascade impactor is a typical sampler for airborne viable microbial particles study.

Although bacteria grow over time, some articles reported initial seeded concentration in the fill water while others reported day-to-day concentrations during the experiments; thus, the final air concentrations varied significantly (Figure 6A). The data in Figure 6A represent total bacteria concentrations from a 6-stage Andersen impactor, with varying experimental time from 30 min to 9 days. The poor R-sq of linear regressions of bacteria concentrations in air versus in water is due to the inconsistent reporting of seeded strain concentrations with various operation time (i.e., 0–14 days[22] and 10–30 min[45,47]) and also various investigated experimental conditions of different measurement methodology (e.g., different species studied, different cultivation methods, and fill water matrix of distilled water, or sterile tap water, or nonsterile, untreated tap water, see Table 2). Yang et al.[22] and Oie et al.[47] showed approximately 10-fold increase in fill water bacteria concentration after 150 min and 48 h ultrasonic humidifier operation compared to initial fill water bacteria concentrations, and the rapid growth may be facilitated by dispersion of the formed colonies by ultrasound energy within the humidifier reservoir.[22] Endotoxin, a toxic organic chemical produced from microorganisms, shows positive proportional relationship between water and air concentrations (Figure 6B).[43]

3.4.2 | Size distributions of emitted microorganisms

For microorganisms, the majority were in the smallest collection size bins of the Andersen cascade impactor of 650–1100 nm and 1100–2200 nm. Table 2 shows the size distributions from two articles

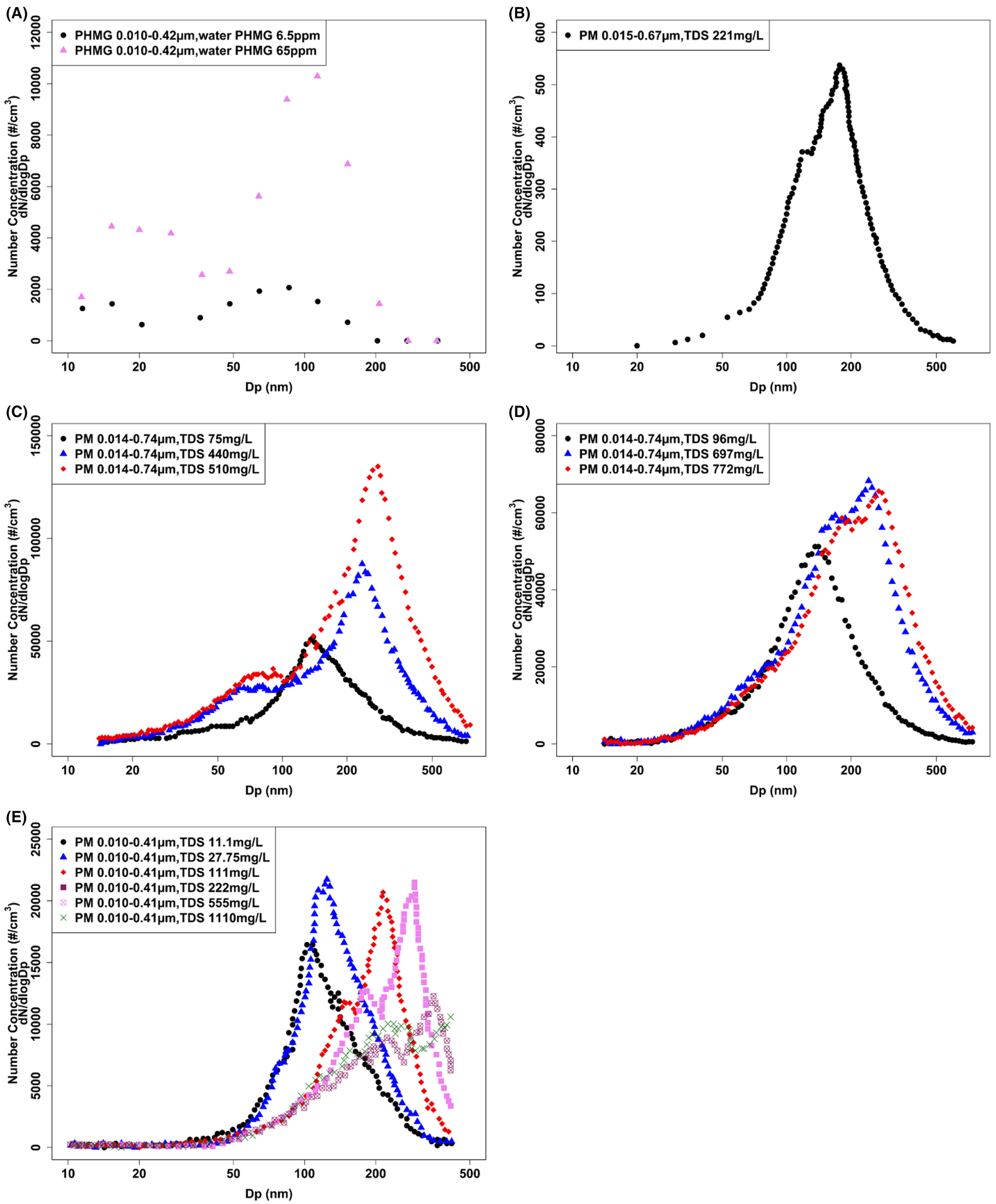

FIGURE 3 Particle size distribution of emitted humidifier particles measured by scanning mobility particle sizer. *X*-axis is in log scale. (A) PHMG generated humidifier particles.[34] (B) tap water generated humidifier particles.[35] (C) tap water of three water qualities generated humidifier particles.[17] (D) tap water of three water qualities generated humidifier particles.[18] (E) $CaCl_2$ solutions generated humidifier particles.[36]

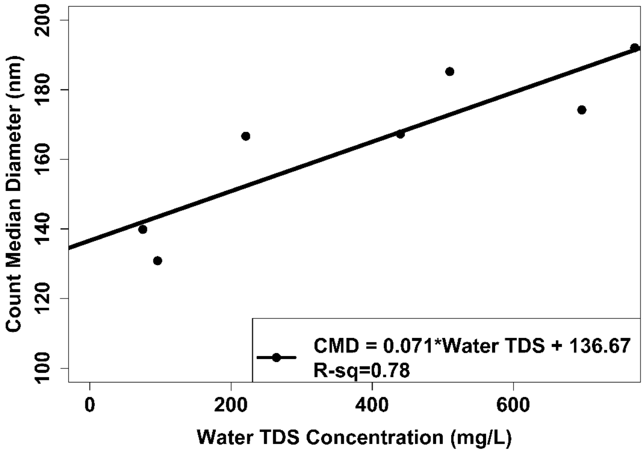

FIGURE 4 Linear regression of fill water total dissolved solids and count median diameter of emitted humidifier particles.[17,18,35]

describing emissions of various strains of bacteria from ultrasonic humidifiers into room air; the majority of bacteria emitted were in the 650–3300 nm range.

4 | DISCUSSION

4.1 | Indoor air quality degradation from ultrasonic humidifier emissions

Indoor air quality correlates to human health, and the risk assessment of human health requires comprehensive understanding of exposure from various contaminant sources.[21,25–27,48] Government agencies (USEPA[49] and Korea Centers for Disease Control and Prevention[50]) have identified ultrasonic humidification devices as an indoor contaminant source that affect human health. Ultrasonic humidifiers emit more particles and inorganic contaminants present in tap water than do evaporative/thermal humidifiers.[3] This systematic review summarized published water quality and air quality data associated with ultrasonic humidifiers, correlating them with linear regression analysis. Dissolved and particulate waterborne constituents in the fill water will be emitted into indoor air by ultrasonic humidifiers and degrade indoor air quality, including PM, asbestos, metals, and microbes.

For all included PM studies, the ultrasonic humidifier-generated PM levels at steady-state in a room or chamber, and PM levels exceeded the USEPA ambient air standard of $PM_{2.5}$. The submicron emitted PM (CMD <250 nm, Table 1) can deposit in the human respiratory tract and penetrate to the deep lung alveolar region.[14,18] There is strong linear relationship between fill water TDS or metals and emitted PM in the indoor air, influencing the mass concentration, diameter, and size distribution. Well-ventilated rooms have relatively lower concentrations of PM levels, indicating higher ventilation rate will decrease the concentration of emitted PM indoors.[16,18] Even though available data are limited, there are also strong linear relationships between the soluble humidifier biocide PHMG or asbestos fibers in fill water in room air.[34,37,38]

For microorganism and endotoxin emissions, the relationships between fill water and emitted airborne microbes are not as strong as that of PM from TDS or minerals/metals. *Pseudomonas*, pathogenic *Brevundimonas*, *Acinetobacter*, and *Legionella* were enriched after ultrasonic humidification compared to those in the initial room air.[22] A ranking of exposure routes to *Legionella* present in tap water, ranked ultrasonic humidifiers as the highest exposure route compared to drinking, showering, and flushing toilets.[44] Another article identified major fungal species in an experimental apartment air were *Penicillium*, *Aspergillus*, *Cladosporium*, and *Alternaria* in the room air and on wall paper after ultrasonic humidifier use.[23] The inhaled microbial emissions may cause allergies and fever-like symptoms.[43,51] The role of ventilation in microbial exposure via ultrasonic humidifiers in a room remains unknown, since the data show high variability in different room conditions and reproduction of the microorganism is a compounding factor.

4.2 | Health implications from ultrasonic humidifier exposure

If present in fill-water, inorganic metals such as Pb will be emitted in the airborne PM, and the inhalation exposure may increase blood Pb in children, causing impaired neurodevelopment in children and even lung cancer.[52] In addition, inhaled Mn may transport through olfactory-brain barrier, and deposit in the brain, causing neurotoxicity.[53] Inhalation risks may exceed ingestion risk for As, Pb, and Mn when these neurotoxic metals are present in tap water that is consumed daily and also used to fill an ultrasonic humidifier that is used 8-h per day.[54] A study exposed mice to ultrasonic humidifier filled with high silica water, and found silica particles in mouse alveolar tissues, with mitosis dysregulation of genes, cell adhesion molecules, and endocytosis.[36]

The misuse of the humidifier biocide of PHMG simultaneously with ultrasonic humidifier operation resulted in >100 deaths of pregnant women and children, and a study showed positive associations of lung injuries in human patients and PHMG exposure.[55] The humidifier biocide PHMG was correlated with interstitial lung disease in children,[56] indicating that improper use of ultrasonic humidifiers can cause adverse health effects.

There were two case reports of humidifier-related hypersensitivity pneumonitis found in adult females, with similar symptoms of fever, coughing, and dyspnea.[51,57] Another case report illustrated a 6-month infant with pneumonitis and nonreversible obstructive lung injury from inhalation exposure to minerals aerosolized from an ultrasonic humidifier, when the investigation showed mineral deposition on the floor in the closed bedroom.[58]

A limitation of this review is due to the heterogeneity of available fill water quality data, air quality data, and ventilation data; a meta-analysis is not feasible; thus, a summary of published data is

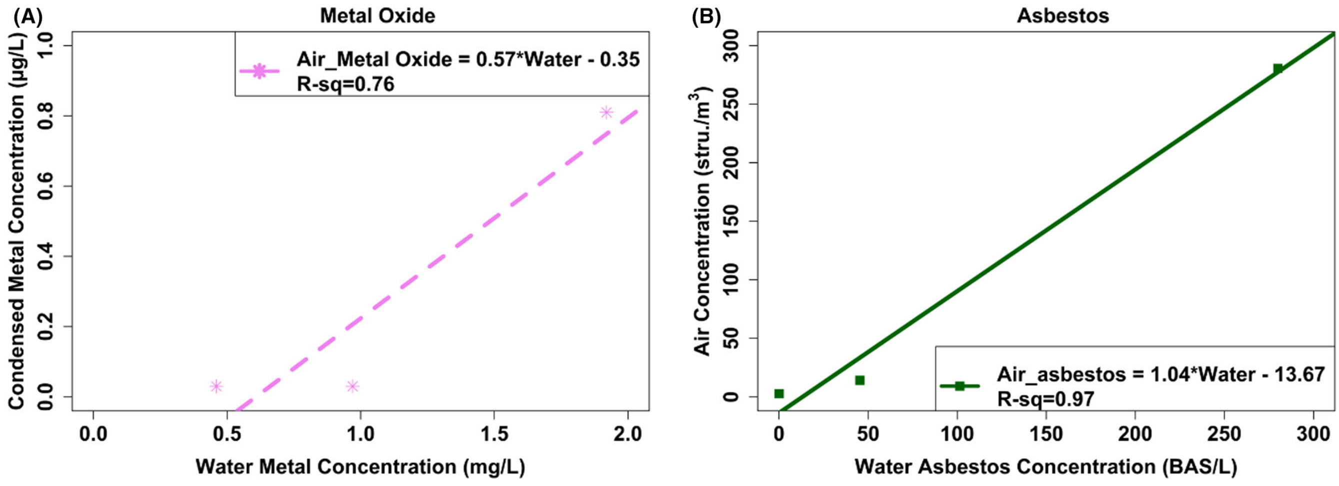

FIGURE 5 Linear regressions on the mass concentrations of airborne constituents from emissions of ultrasonic humidifier and mass concentrations of waterborne constituents. (A) metal oxides,[1] (B) asbestos (BAS/L = billion asbestos structures per liter).[37]

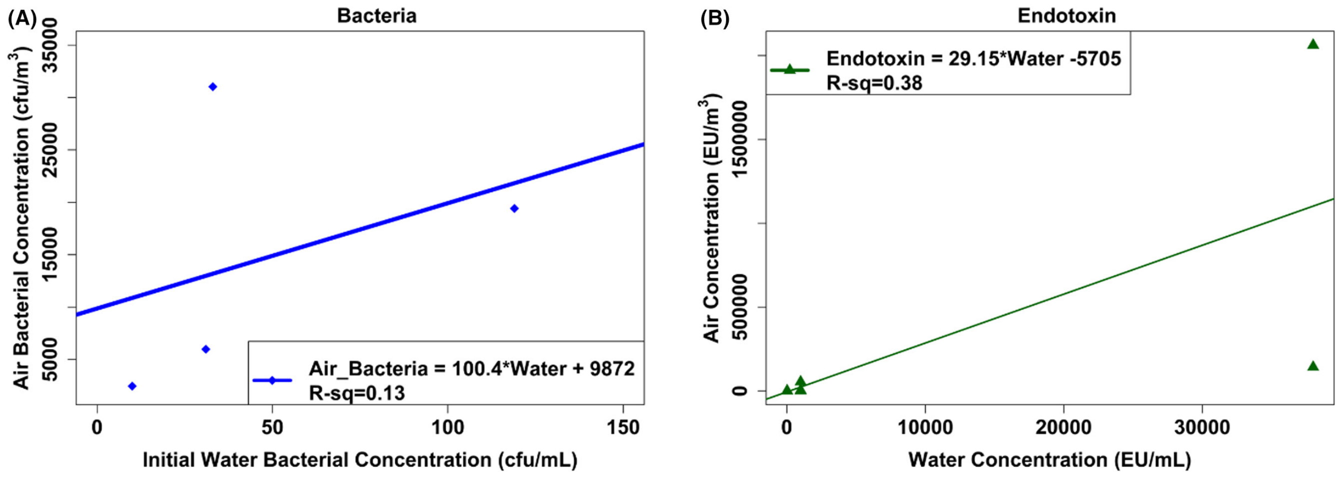

FIGURE 6 Number concentrations of (A) bacteria[22,45] and (B) endotoxin[43] in air and in ultrasonic humidifier fill water initially.

TABLE 2 Size characteristics of emitted bacteria by 6-stage Andersen impactor

	Airborne bacteria counts[a,47] bacteria/m^3 of air	Airborne bacteria[b,45] cfu/m^3 of air	
Particle size bin, nm	*P. paucimobilis*	*M. abscessus*	*M. avium Va14 (T)*
650–1100	21 000	3074	10 389
1100–2100	54 000	2544	7703
2100–3300	11 000	212	954
3300–4700	1300	87	166
4700–7000	670	37	53
>7000	500	25	145

[a]Seeded sterile distilled water with 100 000 bacteria/ml of *Psuedomonas paucimobilis* in humidifier fill water.

[b]Seeded sterile tap water with 31 cfu/ml of *Mycobacteria abscessus* strains and 119 cfu/ml of *Mycobacteria avium* Va14 (T) strains.

presented in this systematic review. Future endeavors on the consistent reporting of humidifier emission parameters and exposure room scenarios are recommended.

5 | CONCLUSION

This systematic review is the first to comprehensively summarize and evaluate results of a wide range of chemical and microbial waterborne constituents emitted from ultrasonic humidifiers. The review demonstrates that ultrasonic humidifier emissions are closely related to the fill water quality, for the investigated dissolved minerals and metals as PM, dissolved humidifier biocide, insoluble metal oxides and asbestos, and microbes. The use of an ultrasonic humidifier not only adds moisture to indoor air, but also releases waterborne chemical and microbial contaminants, increasing the mass concentrations to which humans are exposed. Adverse health outcomes of scarce case reports indicate that lung injury risk occurs, even though the incidence of hospitalized patients is low. Currently, indoor air quality is gaining attention due to the global pandemic of bioaerosols; thus, exceedance of $PM_{2.5}$ and emissions of microbes from ultrasonic humidifiers requires assessment of indoor air quality impacts. More guidance for and possible regulation of humidification devices should be considered.

AUTHOR CONTRIBUTIONS

Andrea M. Dietrich: conceptualization; funding acquisition; methodology; project administration; writing. Wenchuo Yao: formal analysis; methodology; visualization; writing. Daniel L. Gallagher: data curation; formal analysis; software; writing.

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CONFLICT OF INTERESTS

The authors declare no competing financial interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable—no new data generated as this is a review article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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