Abstract: The exposure of people to opportunistic premise plumbing pathogens (OPPPs) such as Legionella, Mycobacterium and Pseudomonas in aerosolised water has been linked to opportunistic infections. Water mist systems (WMS) that are used to cool public places by flash evaporation of tiny water aerosols are gaining prominence in hot climatic regions of Australia. Their potential to be colonised by OPPPs has not been adequately studied. The public health impact of OPPPs is significant, as Legionella caused 63% of waterborne disease case hospitalisations in the United States associated with drinking water systems during 2013–2014, and the incidence of Mycobacterium avium over the same period was 647 cases per 100,000. As WMS are part of premise plumbing, they have structural characteristics that can promote biofilm formation, as well as the presence of free-living amoebae (FLA), low residual disinfection levels, elevated water temperatures and oligotrophic conditions, all of which can promote OPPP inhabitancy. This review highlights the potential public health risks of using WMS as a cooling intervention in public places and advocates for their regulation in places of public assembly and entertainment.

Keywords: opportunistic premise plumbing pathogens; water mist system; Legionella; Mycobacterium; Pseudomonas; Acanthamoeba; Naegleria; health risks

1. Introduction to water mist systems (WMS) used as a cooling intervention in public places

In this review, water mist systems are defined as plumbing mechanisms installed in outdoor public places such as patios and gardens in order to reduce ambient temperatures and promote thermal comfort. The complete assembly of these systems includes a high-pressure water pump and lengths of high-pressure tubing, to which is connected slip lock nozzles at graduated distances. The nozzles are designed to atomise water into tiny aerosols that flash evaporate in the ambient atmosphere, thereby reducing surrounding temperatures by as much as 10 °C and instantly making the thermal environment more comfortable for patrons. Figure 1 shows the typical layout of a water mist system.
Figure 1. Schematic of a typical water mist system used for cooling public places.

Because of their minute particulate size (0.3–10 µm), the aerosols released completely evaporate without wetting any surfaces. The lengths of high-pressure tubing and nozzles are fitted at regular distances under the roofs of covered areas, running around the perimeter of outdoor sitting areas to form a surrounding drape of cool air. A variation of these systems involves the fitting of the header tubing and nozzles to the front of mist fans that can dissipate the cooled air to distances of up to 10 m, which has the advantage of driving away flies and other insects [1]. A study of WMS in Singapore [2] demonstrated that they could achieve thermal comfort at significantly lower energy costs in comparison to conventional air conditioning systems during periods of hot and humid climatic conditions. Dry-bulb temperature reductions of 12 °C have been recorded during studies of these systems [3, 4].

Water mist systems are part of premise plumbing, and the latter has been found to promote the colonisation and regrowth of opportunistic premise plumbing pathogens (OPPPs). A study to determine the most important factors affecting the presence and multiplication of opportunistic pathogens in premise plumbing [5] established that Legionella, Mycobacterium, Pseudomonas and Acanthamoeba have become ubiquitous in these environments, where they have been associated with opportunistic infections. Water mist systems are now popular as an effective and affordable means of achieving evaporative cooling in hot and humid climates. The Pilbara region of Western Australia sits north of the 26th parallel and experiences very hot summer temperatures that average 36–37 °C from November to April and 28–29 °C from May to October [6]. In climate projections for the Pilbara region for 2070, this area is [6] foreseen to have an increasingly hotter and drier climate, with an expected annual average increase of 3 °C in summer and 4 °C in winter as compared to the 1990 baseline. Based on this increase in temperature extremes and the low energy costs associated with the use of WMS for cooling ambient temperatures, it is reasonably expected that the uptake and use of WMS for evaporative cooling in this climatic region may also increase. The increasing global temperatures attributed to climate change have the potential to increase the demand for these systems [7].

The majority of research on the application of WMS for cooling interventions has been experimental and has primarily focused on establishing their operational efficiencies, economies and optimum design parameters [2, 8-11]. In contrast, there has been limited investigation of the public health risks presented by OPPP colonisation of these systems. Whilst acknowledging that WMS using misting fans are effective at reducing ambient temperatures, a study examining the performance of water
misting fans [2] determined that the resultant increase in relative humidity promoted the growth of bacteria and fungi. Extensive research of other premise plumbing installations, such as drinking water systems [12, 13], cooling towers [14-16] (13-15), showers, water taps and faucets [17-20], have established that opportunistic premise plumbing pathogens such as Legionella pneumophila, Mycobacterium avium, Pseudomonas aeruginosa, Acanthamoeba and Naegleria fowleri have become ubiquitous in such systems. American research into the public health risks associated with OPPPs has focused on hospitals and aged care facilities [18, 20-23], whilst some Asian studies have centred on operational efficiency [2, 3]. There is a substantial gap in knowledge regarding the public health risks associated with WMS used for cooling public places, particularly their potential to be colonised by OPPPs and the promotion of their regrowth. In identifying research needs for OPPPs, [24] it has been highlighted that there is a need to investigate environments promoting their growth and multiplication. This review examines and describes WMS used for cooling public places, focusing on their ability to promote the growth and multiplication of OPPPs. We highlight the five major OPPPs implicated in waterborne diseases, namely, L. pneumophila, M. avium, P. aeruginosa, Acanthamoeba and N. fowleri.

2. Opportunistic Premise Plumbing Pathogens and their public health impact

OPPPs are microorganisms which have become ubiquitous in water distribution systems (WDS), including that part of plumbing beyond the supply of water service mains [5, 25, 26]. Because of their tendency to cause illness in people with predisposing risk factors, such as compromised immunity, the elderly and the young, these pathogens have been called “opportunistic” [24, 26]. Some of the major OPPPs which have been associated with WDS and premise plumbing are L. pneumophila, M. avium, P. aeruginosa, Acanthamoeba and N. fowleri [13, 26-30].

2.1. L. pneumophila

L. pneumophila is one of the most recognised OPPPs associated with premise plumbing and several outbreaks of waterborne pneumonic disease called Legionellosis [31-36]. L. pneumophila has been isolated from cooling towers, warm water baths, water fountains [16, 37, 38], showers [39, 40] and drinking water systems [41-43]. This OPPP has also been found to grow in amoebae [44, 45], and this phenomenon has been found to make it resistant to disinfection [46-48].

2.2. M. avium

M. avium belongs to a group of environmental nontuberculous mycobacteria (NTM). These opportunistic pathogens are capable of causing pulmonary diseases in people with compromised immunity, such as those suffering from AIDS [49-51]. The colonisation of this pathogen in premise plumbing has been demonstrated in several studies of potable water systems [52-54], with the bacteria isolated from drinking water systems [55-57], hospital plumbing systems [29, 58, 59] and household plumbing [60]. In a study [61] of 21 isolates of natural waters, it was determined that aerosolisation is a potential route of infection for this pathogen. Another study of transmission pathways for opportunistic pathogens confirmed that aerosolisation of M. avium was possible [62]. M. avium is able to resist disinfection in premise plumbing by its ability to survive inside amoebae [63, 64].

2.3. P. aeruginosa

P. aeruginosa is a hardy and versatile opportunistic pathogen with the ability to adapt and survive a broad range of environmental conditions [65]. This bacterium has a tendency to favour oligotrophic conditions, which enables it to flourish in premise plumbing waters [66]. Transmission
of \textit{P. aeruginosa} can occur through exposure to contaminated water and is known to cause an aggressive pneumonia in people suffering from cystic fibrosis and nosocomial infections in hospital patients [25]. This bacterium has become one of the most commonly isolated infectious bacteria in hospital intensive care units [67], as well as in hospital tap waters [23, 68], shower heads and hydrotherapy pools [69-71]. Chlorine disinfection resistance contributes to this opportunistic pathogen’s survival in premise plumbing [43, 72, 73]. An Australian study to determine the growth of opportunistic pathogens in seven drinking water and six recycled schemes isolated high numbers of \textit{P. aeruginosa} in one of the drinking water systems [26].

2.4. \textit{Acanthamoeba}

\textit{Acanthamoeba} is a protozoan with the ability to live in varied environments, such as environmental and drinking water systems [74, 75], tap water [76], well water [76], hospital waters [77, 78] aquatic facilities [79, 80] and recycled water [26]. \textit{Acanthamoeba} has gained attention as the infectious agent for a central nervous system disease called granulomatous amoebic encephalitis (GAE), which affects people with weakened immunity, as well as \textit{Acanthamoeba} keratitis, an infection of the corneal epithelium [24, 26, 80]. A significant characteristic of \textit{Acanthamoeba} in premise plumbing is its ability to act as a host of OPPPs such as \textit{L. pneumophila}, \textit{P. aeruginosa} and \textit{M. avium} [25, 45, 46, 81-83]. A study of amoeba-related health risks in potable water systems [44] advocated for its monitoring to complement existing water quality monitoring approaches. By acting as a host of other OPPPS in premise plumbing, \textit{Acanthamoeba} can shield them from chlorine disinfection [46, 47, 64, 83-86].

2.5. \textit{N. fowleri}

\textit{N. fowleri}, the only pathogenic species of its genus, has become a major concern because it is the agent of fatal primary amoebic meningoencephalitis (PAM), which is contracted by aspiration of contaminated water aerosols up the nasal passage [87-89]. This free-living amoebae (FLA) has been detected in drinking water systems [26, 88, 90], with domestic water supply systems being implicated in a South Australian outbreak of the disease in children exposed to bathing water [91]. \textit{N. fowleri} has also been detected in recreational waters [92], premise plumbing [93], irrigation systems [94] and rain water tanks in Queensland [95]. This pathogen is resistant to standard chlorine disinfection concentrations [96-98]. Super chlorination is the recommended method for ridding contaminated water systems of this pathogen [99].

2.6. Public health impact of Opportunistic premise plumbing pathogens

The public health impact of OPPPs is significant. It has been estimated that \textit{Legionella} is responsible for almost 2%-15% of patients hospitalised globally with community acquired pneumonia [100]. The American Center for Disease Control (CDC) reported 432 cases of waterborne diseases between 2011 and 2012 [51, 101]. One hundred and two out of the 432 cases were hospitalised, with 66% of the hospital admissions being caused by \textit{L. pneumophila}. The incidence rate for \textit{M. avium} was 647 cases per 100,000 persons, with a higher prevalence in the immune-compromised population [51, 101]. The cost of managing outbreaks of waterborne diseases caused by OPPPs can be significant. A study of healthcare costs related to diseases partly transmitted by water estimated the hospitalisation costs for patients affected by Legionnaires’ disease and NTM in the United States to be $33,336 and $25,985, respectively, making this the highest episode cost associated with the outbreak of waterborne diseases. The World Health Organization (WHO) has reported that cases of \textit{Legionella} infections in Europe alone increased from 1161 per year in 1994 to 4546 in 2004, and in all these cases, the mode of transmission was via the inhalation of contaminated water aerosols [102].
Cases of Legionellosis in Australia are increasing, as shown in Figure 2, with an average of 374 cases being reported annually to the Notifiable Disease Surveillance System (NDSS) in the 10-year period from 2008 to 2018 [103]. The combined reporting of *L. pneumophila* and *Legionella longbeachae* cases in Australia also tends to obscure any trends associated with exposure routes, considering that one is soilborne (*L. longbeachae*) and the other is waterborne (*L. pneumophila*). In Western Australia, the Legionellosis rate varied between 1.5 and 4.5 cases per 100,000 population (2014–2018), with the greatest number of cases in persons aged over 55 years [104].

Figure 2. Annual reported cases of Legionellosis in Australia (2008–2018), adapted from the Department of Health, National Notifiable Disease Surveillance System [103].

FLA are now regarded as emerging pathogens of public health importance (PAM) [105]. A total of 19 water-related PAM cases were recorded in Australia between 1960 and 1980 [95], with 111 cases of the same infection being recorded in the United States between 1962 and 2008 [106]. In spite of its common occurrence throughout the world and its high case fatality rate, PAM disease is not listed as a notifiable waterborne disease in several countries [107, 108]. A survey of microbial keratosis was undertaken in Queensland between 2005 and 2015, and researchers estimated the case rate to be 0.66 cases per 10,000 people, with the most common causative agent being *P. aeruginosa* (17.7%), while *Acanthamoeba* accounted for 1% of cases [109]. Opportunistic infections caused by *M. avium* and *P. aeruginosa* may be underestimated because they are not notifiable in most countries [51]. In Australia, NTM infection, inclusive of *M. avium*, is a notifiable disease in Queensland [110]. In 2015, the notification rate for NTM was 25.9 cases per 100,000 population [110]. There have been fewer than 300 *N. fowleri* infections worldwide since it was first identified in 1965, and the most recent case in Australia was reported in 2019 [111].

3. Water mist systems, bioaerosol formation and inhalation risk

The ability to atomise pressurised water and release it into the ambient air as aerosols has already been discussed as the key feature by which WMS cool ambient temperatures in public places to achieve thermal comfort. The aerosols normally fall in the 0.3–10 µm size range, and those measuring 5 µm or less can be deposited into the lungs by inhalation and cause infections [112].
Inhalation of bioaerosols as the route of infection for OPPPs has been investigated in a number of studies. Outbreaks of Legionellosis have been linked to the exposure and inhalation of *L. pneumophila* released from cooling towers [113-115], air scrubbers [116], decorative water fountains [117] and air conditioning [36].

Inhalation of aerosols contaminated with *Mycobacterium* can cause granulomatous respiratory diseases [24]. A study investigating NTM growth and aerosol formation from 18 warm water pools established that 76% (n = 18) of air and water samples tested positive for this OPPP [118]. *Mycobacterium* has also been isolated from drinking water distribution systems [52, 54] and household plumbing [60, 119]. *P. aeruginosa*, the other OPPP found to colonise and grow in water distribution systems and premise plumbing [13, 18, 30, 120], shares similar characteristics to *L. pneumophila* and *M. avium* that make it transmissible by inhalation of aerosols [68, 121]. Inhalation of water aerosols containing amoeba species can cause a number of infections, such as PAM caused by *N. fowleri* [122] and GAE caused by *Acanthamoeba* [80].

Although there are a significant number of studies on the inhalation risk of OPPPs residing in engineered water systems such as cooling towers, scrubbers, drinking water distribution systems, hospital plumbing and so forth, an understanding of the magnitude of this risk in WMS used as a cooling intervention in public places is still lacking. The sampling and analysis of bioaerosols generated by WMS may help in understanding and describing this inhalation risk and the potential for skin and eye infections associated with aerosolisation, since infectious organisms could be directed into eyes, ears and damaged skin (burns, blisters and rashes).

4. Water Misting Systems and factors promoting colonisation and growth of OPPPs

4.1. Biofilm formation

The formation of biofilms in premise plumbing systems has been identified as a significant factor in OPPP colonisation potential [24, 25, 123]. Being engineered water distribution systems, WMS used for cooling intervention in public places form part of premise plumbing; hence, they present similar risk factors of biofilm formation and colonisation by OPPPs. Biofilms are complex heterogeneous colonies consisting of bacteria, fungi, protists and other microbial organisms that grow as native communities in water distribution or storage systems [124], as well as other terrestrial environments such as medical devices [125] and food preparation surfaces [126, 127]. They have been referred to as aftergrowth, consisting of a fine layer of microorganisms living in aquatic conditions joined in an extracellular matrix of various shapes and sizes of filaments and deposits [24, 128-130]. The probability of biofilms forming on the internal surfaces of WMS is high considering the presence of copious amounts of nonsterile water which is in constant contact with internal surfaces as it circulates in the system during operation [131].

This process of biofilm formation, also known as biofouling [131], is possible due to various extreme environmental conditions of temperature, pH and pressure that may exist in these water distribution systems [132]. The biofilms form an ecological niche for the OPPPs because of their ability to provide conducive and nutritive conditions for microbial growth, as well as protection from disinfection chemicals and other bactericidal agents [5]. The OPPPs residing in biofilms of water systems are capable of being released into the water phase and thus become significant sources of waterborne pathogens [133]. A study of biofilms in a drinking water system [134] determined that almost 95% of the microbiological population in drinking water systems reside in biofilms as compared to approximately 5% in the water phase. This means that the standard approach of collecting water samples from the water phase only is unable to assist in understanding the extent of biofilm growth in water distribution systems [134]. The sampling and analysis of biofilm samples from WMS used as a cooling intervention is recommended to provide an insight into their potential as sources of OPPPs.

4.2. Temperature
Elevated water temperatures in distribution systems have been found to promote the growth of OPPPs [25, 129, 135, 136]. According to Falkinham et al., survival at elevated water temperatures is one of the critical adaptation features which enables *L. pneumophila*, *M. avium* and *P. aeruginosa* to thrive in water systems [51]. The WMS used for cooling public places in the Pilbara region of Western Australia are exposed to extremes of summer temperatures averaging 36–37 °C from November to April and 28–29 °C from May to October [137]. These hot climatic conditions often result in equally elevated water temperatures in Pilbara water distribution systems, as shown in Figure 3 [138], which could speed up the colonisation and spread of OPPPs in these systems.

![Drinking water temperature Jun 2018-May 2019](image)

**Figure 3.** Water temperatures in a Pilbara water distribution system in the study area, June 2018 to May 2019 [138].

A study of potable and reuse water schemes operating in the various climatic regions of Australia [26] established the important part played by higher water temperatures in the increased occurrence of *N. fowleri* and *L. pneumophila* in those systems situated in warmer climates. Based on these observations, it can be reasonably expected that the water temperature profile of WMS used for cooling public places in this warm climatic region will mirror that shown in Figure 3 [138]. Determining the water temperature profile of WMS is important to understand its possible influence on the potential of OPPP colonisation and regrowth. In addition to the effect of warm temperatures discussed above, the presence of FLA in water distribution systems can aid the regrowth of OPPPs [43, 129, 139, 140].

### 4.3. Presence of FLA

The part played by FLA in amplifying the number and virulence of OPPPs in engineered water systems is now widely acknowledged [13, 83], with *Legionella* and *Mycobacterium* showing a greater ability to proliferate in this manner [76]. The monitoring of amoeba in drinking water systems as part of a water quality monitoring program has also been advanced as an effective measure [44, 105].

Through a process of phagocytosis, FLA such as *Acanthamoeba* in water distribution systems [13] feed on other OPPPs including *Legionella*, *Mycobacterium* and *Pseudomonas* [141, 142]. When subjected to unfavourable growth conditions, the FLA develop into cysts with thick walls which shield the
OPPPs growing in them from destruction by disinfectants such as chlorine [76, 83, 141, 142]. Furthermore, the ability of this beneficial relationship to increase the virulence of the OPPPs growing inside the FLA has been well documented, particularly for *Legionella* [25, 26, 51, 143] and *Mycobacterium* [82, 144]. In contrast, phagocytosis of *Pseudomonas* is restricted by its ability to produce a secretion which destroys the amoeba [145].

In view of the important part played by FLA, particularly *Acanthamoeba*, in the regrowth and amplification of OPPPs, as well as their virulence in water distribution systems, it is important that WMS used for cooling public places in the Pilbara region of Western Australia are investigated for this protozoan [44]. The water quality monitoring data, shown in Table 1, obtained from a Pilbara water distribution system indicated that approximately 10.6% (n = 33) and 3.2% (n = 7) of water samples collected between 2016 and 2018 tested positive for thermophilic amoebae and thermophilic *Naegleria*, respectively, which encompass *Acanthamoeba* and *N. fowleri* [146, 147].

**Table 1. Occurrence of thermophilic amoebae and thermophilic Naegleria in a Pilbara drinking water system in the study area, 2016–2018 (n = 216) [146, 147].**

<table>
<thead>
<tr>
<th>Year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermophilic amoebae +ve</td>
<td>13</td>
<td>13</td>
<td>7</td>
<td>33</td>
</tr>
<tr>
<td>Thermophilic <em>Naegleria</em> +ve</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>No. of samples -ve for both microorganisms</td>
<td>55</td>
<td>57</td>
<td>64</td>
<td>176</td>
</tr>
<tr>
<td>Totals</td>
<td>72</td>
<td>72</td>
<td>72</td>
<td>216</td>
</tr>
</tbody>
</table>

**4.4. OPPPs and resistance to chlorine disinfection**

Chlorine has been successfully used to disinfect water over the last 100 years [148]. It has been described as one of the most important public health interventions of the century [149]. At the right pH (6.5–8.5) [150], temperature (20–29 °C) [151] and turbidity (1 nephelometric turbidity unit (NTU)) [150], chlorine is able to provide an adequate residual disinfectant effect. However, several studies have demonstrated that under certain environmental conditions, OPPPs can become resistant to conventional water disinfection, particularly chlorine and its derivatives [43, 46, 64, 81, 83, 152]. *M. avium* has demonstrated resistance to chlorine disinfection when engulfed by *Acanthamoeba* [26, 63]. Biofilms also shield this pathogen from chlorine disinfection [25, 64]. The presence of slime or biofilm adds to the survival of *P. aeruginosa* in the presence of chlorine disinfectant [72, 153, 154].

Most of the studies of OPPP resistance to chlorine disinfection have focused on drinking water systems, recycled water schemes and cooling towers. The impact of this phenomenon on WMS used as a cooling intervention in public places has not been adequately studied. Most WMS are connected to scheme water supplied by licensed and regulated operators [155]. However, due to geographical location and remoteness, a few of these systems are connected to onsite borehole water supplies that are locally managed. Chlorination is the most common means of disinfection for Australian water supplies, with a minimum target of 0.5 mg/L residual chlorine recommended [150]. The larger scheme water operators use chlorine dioxide for disinfection, while the smaller ones prefer liquid sodium hypochlorite or calcium hypochlorite. The presence of FLA is an environmental variable that can promote bacterial pathogen resistance to chlorine disinfection [43, 46, 83, 141]. Bacteria engulfed by *Acanthamoeba castellanii* can survive exposure to residual chlorine concentrations of 10 mg/L over 24 h and form cysts when exposed to concentrations greater than 4 mg/L [81].

Since chlorination is the main form of disinfection for water supplies connected to WMS, an investigation of the effectiveness of this disinfection method in preventing or limiting the colonisation and regrowth of OPPPs in these systems is warranted.

4.5. OPPPs and low total organic carbon (TOC) concentration (Oligotrophic conditions)

The ability of OPPPs to thrive in premise plumbing systems with low carbon concentrations is another important characteristic of their persistence [13, 124, 156]. Low-carbon or oligotrophic environments are characteristic of most premise plumbing and drinking water systems [5]. The nitrifying bacterial autotrophs present in low-carbon waters fix available carbon, subsequently making it available to heterotrophic organisms such as OPPPs, which are then able to metabolise the carbon [5, 157]. Through this process, low-carbon water environments existing in premise plumbing systems are able to select for OPPPs over other microorganisms. A positive relationship with organic carbon has been established between *L. pneumophila* [158], *P. aeruginosa* [66] and *M. avium* [159].

To better understand the impact of oligotrophic conditions on the ability of OPPPs to colonise and regrow in these WMS, the sampling and analysis of water from these systems for TOC concentration is needed to determine potential sustainability.

5. Conclusion

The emerging use of WMS as a cooling intervention in public places is increasing due to their ability to quickly achieve thermal comfort at lower operational costs. These systems share similar characteristics of biofilm formation, elevated temperatures, growth of FLA and low organic carbon concentration with premise plumbing, from which colonisation and regrowth of OPPPs such as *L. pneumophila*, *M. avium*, *P. aeruginosa*, *Acanthamoeba* and *N. fowleri* has been established. The WMS aerosolise water into tiny inhalable particles which can then transmit pathogens to hosts through inhalation, as well as through contamination of surfaces and the skin/eyes. An investigation of the health risks associated with the use of WMS as a cooling intervention is warranted to better understand their public health impact and inform strategies to manage the risks they may pose.

**Conflict of interest**

The authors declare no conflict of interest.

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