

Breathing Beneath the Surface: A Review of Airborne Toxins in Indoor Pools

By Camryn E. Williams

AUTHOR BIO

Camryn Williams is a rising senior at Kent Denver High School in Denver, Colorado. She is a competitive swimmer for the Denver Hilltoppers and serves as a head coach for a Special Olympics swim team in the Denver region. She hopes to study sustainability and data science as well as conduct more projects in these fields in the future.

ABSTRACT

Indoor pool facilities rely on chemical disinfection and mechanical ventilation systems to maintain water and air quality, but these same processes can generate harmful byproducts that threaten public health. This literature review synthesizes research on disinfection by-products, including their formation, behavior, and associated health effects. Studies consistently demonstrate that disinfection by-products contribute to the increased risk of respiratory irritation and asthma in swimmers. The more drastic effects have linked disinfection by-product exposure to the elevated risk of cancer, with elite athletes and children identified as the most vulnerable groups. Ventilation effectiveness and pool occupancy rate significantly influence airborne DBP concentrations. Although alternative treatment methods such as ozonation and UV radiation can reduce disinfection by-product levels, they introduce new challenges, including increased chlorine demand. These findings highlight the need for improved treatment technologies and stricter air quality policies to mitigate health risks in enclosed aquatic environments for pool users and employees.

INTRODUCTION

Water treatment in indoor pool facilities is a critical safeguard for public health, far exceeding simple maintenance. While pools serve as vital hubs for physical activity and rehabilitation, they are essentially “living” chemical environments. Without rigorous treatment, swimmers face risks ranging from waterborne pathogens to severe respiratory distress caused by volatile chemical byproducts.

Regulatory Standards and Oversight

In the United States, pool safety is regulated through a patchwork of state and local health departments rather than a single federal mandate. However, the Centers for Disease Control and Prevention (CDC) maintains the Model Aquatic Health Code (MAHC). Though voluntary, the MAHC serves as the gold standard for pool legislation, providing evidence-based guidelines for chemical concentrations, ventilation rates, and lifeguard requirements. Over the last decade, these standards have shifted significantly toward “secondary disinfection” requirements (like UV or Ozone) to combat chlorine-resistant pathogens like *Cryptosporidium*, marking a transition from simple “clear water” aesthetics to complex microbiological safety.

The Evolution of Pool Sanitation

The transition to chemical treatment began in 1897 when a British scientist Sims Woodhead utilized a bleach solution to sterilize water during a typhoid outbreak (Krough, 2017). By the early 20th century, chlorine became the primary agent for rendering water potable, eventually migrating to recreational use due to its high efficacy and low cost (Clean Water and Clean Air in Modern Aquatics Facilities – PUPN, 2024). However, modern science recognizes that sanitation is a two-part process: chemical neutralization of bacteria and physical filtration of organic matter (Jarin et al., 2025).

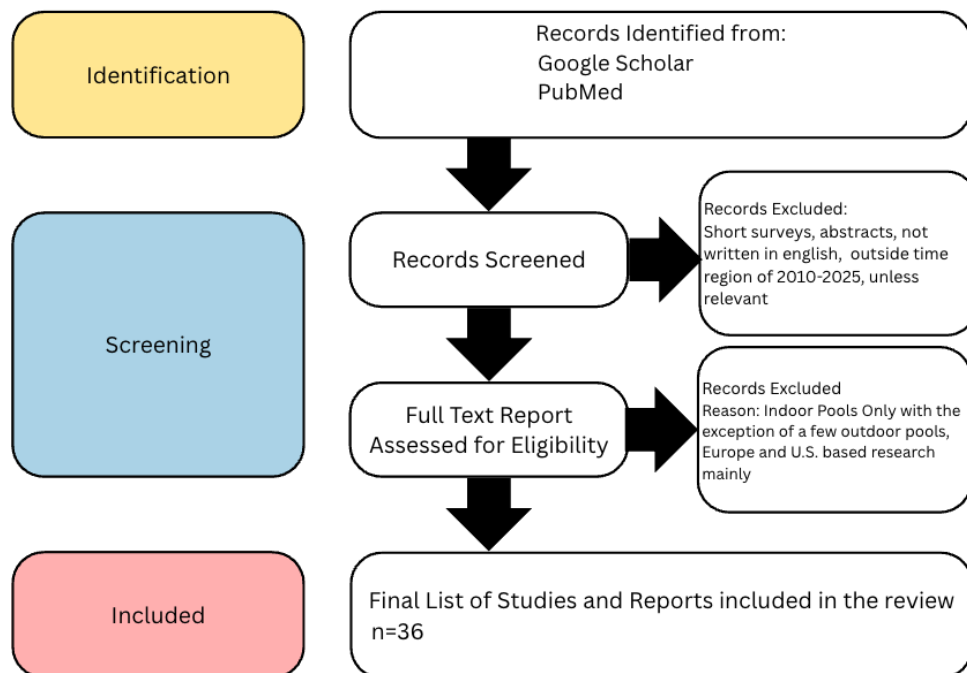
Global Perspectives and Risks

While the U.S. relies heavily on chlorine, international standards often prioritize different mechanisms. European facilities usually emphasize ozone or UV filtration to reduce chemical reliance (Tiwari et al., 2021). By contrast, Japan prioritizes mineral content within pools and natural hygiene in treating pool water (Olsen, 2007).

Despite these advancements, the margin for error remains slim. Since 1965, when 23 children were hospitalized in Illinois due to a tank valve failure, chemical accidents have remained a persistent threat (“23 Gassed While Swimming,” 1965). In 2018, a New York facility experienced a “slug” of toxic chlorine gas when a chemical feeder failed to shut off, mixing chlorine with acid in the recirculation lines (Esschert, 2019). Between 2007 and 2017, an estimated 13,508 pool-chemical-related injuries occurred in the U.S. alone, highlighting a critical paradox: the very systems designed to protect public health can, if mismanaged, become the source of severe illness.

METHODS

Literature Review



To evaluate the current state of indoor pool safety, a comprehensive literature review was conducted using databases including Google Scholar, PubMed, JSTOR, and Taylor & Francis Publications.

Search Strategy

Keywords included “Indoor Pools,” “Pool Sanitation,” “Hypochlorous Acid” and “Disinfection Byproducts.” Research was primarily limited to peer-reviewed journal articles published between 2010 and 2025 to capture the most recent advancements in secondary disinfection and air quality monitoring.

Inclusion and Exclusion Criteria

A primary distinction was made between indoor and outdoor aquatic environments. Outdoor pools were largely excluded from this review due to two factors:

1. UV Degradation: Sunlight naturally breaks down chlorine and certain byproducts, a variable not present in indoor settings.

2. Atmospheric Exchange: Outdoor pools benefit from infinite air dilution. In contrast indoor pools exist in a “closed-loop” air system where volatile organic compounds (VOCs) and chloramines accumulate just inches above the water’s surface, the exact zone where swimmers breathe.

By focusing on indoor facilities, this research targets the specific risks associated with “enclosed-air” chemical accumulation, which is the leading cause of respiratory inflammation and occupational asthma among competitive swimmers and lifeguards.

RESULTS

The intersection of water chemistry and air quality manifests in several documented health risks, categorized by the nature of the chemical exposure.

Water Quality

Water Treatment

Chlorine is a very common disinfectant in the U.S. because it kills bacteria effectively for a low price (US EPA, 2022). On the molecular level, chlorine has the ability to disrupt a bacterium's or virus's structure through oxidation. Oxidation uses compounds that attack and damage bacteria's cell walls and DNA, effectively killing or inactivating them (Jarín et al., 2025). While chlorine is an effective sanitation method, chlorine’s power as a disinfectant is hindered by its interaction with other disinfection processes and organic matter. Chlorination byproducts (CBPs) and disinfection byproducts (DBPs) result from chlorination combined with urea, putting swimmers at risk for adverse health effects (Couto et al., 2021b). Other factors, such as pH, sunlight, and the presence of specific contaminants, can reduce chlorine’s effectiveness, requiring additional means of sanitation for the given pool. UV radiation combined with chlorination treatments post-sanitation has proven to increase DBPs in a given pool space. Only through oxidation, ozone generators, and intense UV radiation are the majority of these harmful substances destroyed every time the disinfection process occurs. All of these methods of disinfection result in a reduction in the concentration of chlorine because they are destroying everything present in the pool water (Fernández-Luna et al., 2016). It is a complicated process wherein the sanitation processes, which are needed to eradicate harmful substances and pathogens, also reduce each other's effectiveness.

Chlorination By-Products

Urea secretion is a normal human process, as it is a component of urine, sweat, or saliva. In pools, the urea produced by pool-goers interacts with a chemical typically used in water treatment called hypochlorous acid. The interaction of urea and hypochlorous acid leads to the harmful production of CBPs such as chloramines and trihalomethanes (Couto et al., 2021a). Several studies have found that higher concentrations of CBPs in pool water are associated with higher concentrations of CBPs in the surrounding air. Researchers have noted that human exposure occurs through dermal absorption, inhalation, and ingestion (Couto et al., 2021a; Kalita et al., 2024).

Researchers have identified chloramines as the primary byproducts of the hypochlorous acid and urea reaction. There are a total of three inorganic chloramines. Researchers have found that trichloramine, in particular, is 400 times more volatile than the other two chloramines (dichloramine and monochloramine) (Wastensson & Eriksson, 2020). Specific research on chloramines has revealed that trichloramine is immiscible with water and evaporates approximately 300 times faster than monochloramine and 100 times faster than dichloramine from water to air transfer (Wastensson & Eriksson, 2020). These airborne CBPs have been associated with increased risk of asthma as well as potent sensory irritants that cause eye and upper respiratory tract irritation (Couto et al., 2021b). CBPs are reported to occur only when chlorination is used as a means of treatment.

Disinfection Byproducts

Disinfection byproducts are a result of all water and sanitation treatments, with CBPs identified as a chlorine-specific subset. Studies exhibit that DBPs can evaporate into the surrounding air, contributing to poor indoor air quality (Lee & Blatchley, 2022; Wastensson & Eriksson, 2020). Multiple studies from as early as 1990 have linked DBP exposure to adverse health outcomes, including childhood asthma and respiratory diseases (Aggazzotti et al., 1990; Bernard et al., 2006; Helenius et al., 2002; Jacobs et al., 2007; Jarin et al., 2025; Kalita et al., 2024). More recently, other studies have linked a connection between DBP exposure and carcinogenic effects over long repeated durations of exposure (Boraczyński et al., 2025; Donat-Vargas et al., 2024; Wagner & Plewa, 2017).

Several studies have investigated UV treatment of pool water and its impact on DBP formation. One study, from 2015, reported that UV treatment followed by chlorination accelerated DBP formation (Spiliotopoulou et al., 2015). Another study conducted in 2016 confirmed this finding and additionally noted that ozonation before UV treatment reduced the need for chlorine and decreased DBP formation (Cheema et al., 2017).

Filtration System

Research describes water treatment as occurring through multi-level filtration systems that separate contaminants from water before returning it to the pool. Filter beds are reported to be cleaned on average every 2–4 days by trained personnel to maintain sanitary water quality (Studziński et al., 2021). Following filtration, chlorine or some other treatment means is applied before the water reenters the pool (Lee & Blatchley, 2022; Studziński et al., 2021). Some studies report that UV treatment can be incorporated into filtration systems while the water is in the filter beds (Cheema et al., 2017; Zare Afifi & Blatchley, 2016).

Air Quality

Volatile Compounds

CBPs and DBPs are both considered volatile compounds (VOCs). High temperatures, small enclosed recreation spaces, and an increased number of pool users all contribute to higher concentrations of VOCs in the recreation space. Higher temperatures are reported to increase pool evaporation rates, and

foster pathogen growth, increasing airborne contaminant levels (Mohamed et al., 2025). Small pool volumes and enclosed spaces result in greater accumulation of aromatic VOCs. This increases the risk of inhaling harmful chemicals into the airways. Finally, increased numbers of pool users are one of the strongest predictors of heightened concentrations of VOCs in a recreation space's air. The more people using a given pool, the more urea is secreted, interacting with chlorine sanitation methods. Exorbitant activity rates from competitive swimmers also increase this concentration (Lee & Blatchley, 2022; Mohamed et al., 2025).

Ventilation

VOCs are more heavily concentrated in poorly vented recreation facilities. Effective ventilation of indoor pools requires continuous 24-hour operation of air-exchange systems in order to maintain safe conditions (Hanafi et al., 2023). Air conditioning systems (ACS) are reported to be a required form of ventilation in indoor pool spaces to maintain the air and pool water temperature (Hanafi et al., 2023; Mohamed et al., 2023; Rojas & Grove-Smith, 2018).

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) classifies indoor pools as a hazard of Air Class 2. To be classified as an Air Class 2 means the air contains moderate contaminant concentration and mild sensory irritants. When ventilation systems malfunction or are ineffective, the air quality can shift toward Air classes 3 and 4. Air Classes 3 and 4 are described as highly objectionable fumes containing dangerous particles or bioaerosols (Standards 62.1 & 62.2, n.d.). Studies emphasize that effective ventilation is critical for maintaining safe levels of bioaerosols in indoor pool environments.

When indoor swimming pool HVAC systems don't effectively circulate air or regulate temperature, pool users are at increased risk of exposure to VOCs (Hanafi et al., 2023). A recent study found that poor air and water circulation issues can lead to the formation of "dead zones." These dead zones are found to foster pathogen growth and uneven disinfectant distribution, causing microbial blooms. These blooms evaporate at a significantly higher rate, contributing to a higher concentration of volatile compounds in the air (Jarin et al., 2025).

HVAC system failures are often caused by mold buildup, resulting from high temperatures, humidity, continuous ventilation, as well as aging infrastructure. In a study conducted in Greece, 59 of the 72 indoor pools were found to have air circulation deficiencies (Mplougoura et al., 2025). When ventilation systems break down or are offline for extended periods of time, the enclosed recreation space becomes extremely concentrated with DBPs, which is associated with high humidity and temperatures (Hanafi et al., 2023; Rojas & Grove-Smith, 2018). Without functioning HVAC systems, indoor pools become hazardous spaces, where harmful airborne chemicals can reach unsafe levels for swimmers and staff alike.

Human Health Implications

Pathogenic Hazards and Chlorine Resistance

Chlorine-resistant parasites –ones that are not killed in the disinfection process– such as *Cryptosporidium*, a commonly associated pathogen in outbreaks from swimming pools, can survive in pools for 3.5-10.6 days (Jarin et al., 2025). This window of survival allows for widespread infection even in facilities that maintain standard chlorine levels.

Genotoxicity and Carcinogenic Risks

The health effects of DBPs and CBPs are the most harmful regarding pool user safety. Researchers in the past decade have studied a multitude of DBPs in pools that incorporate chlorine into their sanitation process. Over one hundred of the most common DBPs in chlorinated pools are genotoxic, and more than twenty are carcinogenic (Abilleira et al., 2023). Genotoxicity refers to the ability of a substance to damage DNA, which can result in mutations of human cells and increase the risk of cancer, similar to that of carcinogenic DBPs. Carcinogenic DBPs are associated with an increased risk of certain cancers, particularly bladder and gastrointestinal cancers such as colon cancer (Jarin et al., 2025). Studies have established a direct correlation between prolonged epidermic contact or inhalation of pool air and increased levels of these compounds in the bloodstream (Jarin et al., 2025).

Other than chlorination as a form of sanitation, studies have proven that pools using bromine are generally found to produce more mutagenic, genotoxic, and cytotoxic DBPs (Daiber et al., 2016; Jarin et al., 2025). Cytotoxic DBPs refer to the ability to harm or kill cells, resulting in tissue damage and organ failure (Allen et al., 2021). Mutagenic DBPs, such as trihalomethanes, induce a cell's ability to mutate, causing a cell's DNA to change (Jarin et al., 2025). This, along with carcinogenic DBPs, increases the risk of cancer because a cell can no longer function properly. The carcinogenic adverse consequences are life-threatening, but the lesser consequences are still significant. Bromine irritates the eyes, skin, and respiratory damage (Daiber et al., 2016; Fernández-Luna et al., 2016).

Respiratory Health

In indoor pools, when DBPs accumulate not only in the water but also in the surrounding air, where they can be inhaled through the nose and mouth, leading to irritation of the eyes, throat, and airways (Jarin et al., 2025; Mplougoura et al., 2025). The risk intensifies during physical activity: as swimmers exercise, their bodies produce sweat and heat, elevating the pool water temperature and increasing the evaporation rate. This process causes DBPs to become more concentrated in the air, especially in poorly ventilated spaces (Aggazzotti et al., 1990; Fernández-Luna et al., 2016). As a result, individuals in these settings, particularly frequent swimmers, face continuous exposure to airborne chemicals that can affect their respiratory health.

Children and babies are especially vulnerable to airway inflammation caused by exposure to indoor pool environments. Studies have linked adolescent exposure to chlorinated water treatment in swimming pools with a significant contribution to the development of asthma and respiratory issues. Over the past two decades, adolescent asthma has significantly increased and is now the most common chronic childhood disease (Couto et al., 2021b). Children aged 7-13 years are the most at-risk demographic when it comes to regular pool attendance. Regularly attending indoor chlorinated pools is associated with a likelihood of developing an airway inflammation condition such as asthma (Couto et al., 2021b; Fernández-Luna et al., 2016). Spas and baby swimming pools, which tend to have higher temperatures for comfort, pose another risk because heat causes DBPs to evaporate, thus increasing their concentration in the air. High amounts of chemicals combined with babies' and young children's lack of bladder training (leading to a chemical reaction of urea and chlorine) cause a high risk percentage of DBPs in the water and air (Kalita et al., 2024; Mplougoura et al., 2025).

High-performance swimmers who train daily at intense aerobic levels are the next most affected demographic. As early as 1990, researchers found that 79% of swimmers training 27-37 hours per week exhibited various respiratory symptoms, compared to 21% of non-swimming controls (Boraczyński et al., 2025; Zwick et al., 1990). In 2002, a study observed lower airway respiratory symptoms in 57% of Finland's National Team swimmers (Dehghani et al., 2002). More recently, a 2022 study of young Italian competitive swimmers found that 47% experienced nasal congestion and 62% reported sneezing, with a clear predominance of upper respiratory symptoms (Zaccarin et al., 2022). Frequent exposure to chlorine and other chemicals in these enclosed environments continues to irritate the respiratory system and may lead to airway sensitization over time (Boraczyński et al., 2025).

These adverse consequences are typically proportional to the time spent in pools that use sanitation chemicals. Multiple studies found that there is a greater probability of perceived health problems in swimmers who have been using swimming pools for more than 2 years (Aggazzotti et al., 1990; Couto et al., 2021b; Spiliotopoulou et al., 2015). Swimmers who use indoor pools for long durations are also more likely to exhibit respiratory and anaphylactic problems (Fernández-Luna et al., 2016; Jarin et al., 2025).

Not only are swimmers and pool users affected by poor air quality, but pool workers are also affected. A 3-month-long study found that pool workers started to show an increased number of respiratory symptoms, including, but not limited to, coughing, wheezing, and dryness in the throat. The workers were more likely to exhibit these symptoms at the end of the three-month period (Westerlund et al., 2019).

DISCUSSION

The findings of this review reveal a critical paradox in aquatic facility management: very chemicals used to ensure microbiological safety are the primary drivers of long-term chemical toxicity. While chlorine remains the number one pool sanitation method in the U.S. for neutralizing pathogens, its secondary reactions with organic matter create a multitude of disinfection byproducts that pose a greater chronic health risk than the bacteria they are meant to suppress.

Air-Water Interdependence

One of the most significant insights from the literature is the “dead zone” phenomenon, which challenges the traditional limitation between water and air science. The data suggests that water chemistry cannot be evaluated in isolation from mechanical ventilation. Because trichloramines evaporate 300 times faster than other variants, they concentrate in a thin, volatile layer directly above the pool surface.

Even a facility with perfect water chemistry can become a hazardous environment if the HVAC system fails to clear the air at that water-air interface. This dead zone is precisely where swimmers breathe most deeply during recreational and physical activity. Consequently, the standard for a safe pool environment must shift from a one-sided lens of water testing, to a multi-dimensional framework that integrates water quality, bather load, and air exchange processes as a singular symbiotic system.

Regulatory Gaps and Vulnerability

The research highlights a clear gap in how current regulations protect vulnerable populations. Current U.S. standards, largely influenced by the CDC’s voluntary Model Aquatic Health Code (MAHC), emphasize the elimination of pathogens like *Cryptosporidium*. However, the findings show that for infants and elite athletes, the treatment meant to kill these pathogens is just as damaging.

The high incidence of occupational asthma and respiratory distress observed in Finnish and Italian national swim teams suggests that even the best facilities, which presumably adhere to the strictest protocol and 24/7 ventilation processes, are struggling to manage the byproduct load generated by high-intensity use. This underscores a need for regulations that account for cumulative chemical exposure rather than just instantaneous bacterial counts.

Multi-Barrier Systems

The evidence regarding UV and Ozone treatment presents a complex challenge. While UV can increase certain DBP formation if used incorrectly, the combination of Ozone followed by UV and low-residual chlorination appears to be the most viable path forward. This European model addresses the genotoxicity of bromine and the volatility of chlorine by reducing the overall chemical demand of the system. By leveraging ozone for primary oxidation and UV for targeted dechlorination, facilities can maintain sterile environments while keeping total DBP concentrations well below the thresholds associated with DNA damage and respiratory inflammation.

LIMITATIONS

The availability limits this review and the scope of published research on indoor pool water and air quality. While the search strategy aimed to capture a wide range of peer-reviewed studies, the inclusion criteria excluded many outdoor pool studies, which may have provided additional insights. Most of the research examined was observational or cross-sectional in design, which limits the ability to establish causality between exposure to DBPs/CBPs and specific health outcomes. While this review pulled studies from across the globe, many of them were conducted in Europe and North America, which may limit the generalization of findings. Finally, because the focus was on chemical byproducts and their health effects, other important aspects of pool safety, such as microbial contamination, socioeconomic

factors affecting facility maintenance, or cost-benefit analyses of alternative treatment systems, were not explored in depth.

CONCLUSION

The presence of DBPs and CBPs in indoor pool environments is more than a technical concern; it's a widespread and deeply underestimated health issue. The very sanitation processes designed to keep pools safe can result in harmful chemical exposure, particularly in enclosed indoor spaces with inadequate ventilation. From chlorinated water reacting with urea to produce hazardous byproducts to the long-term risks of cancer, asthma, and respiratory damage in pool users, the consequences are real. Elite athletes, young children, and frequent swimmers are especially vulnerable, and without improved regulation, these risks will persist.

While this research focused on indoor recreational pools, there are several relevant areas that fall outside its scope but warrant future investigation. Outdoor pools are an example, and while they are better ventilated, they still pose risks from the environment surrounding them and direct sun exposure, potentially altering DBP formation. Another area of research that could be considered is the economic or regulatory challenges of upgrading pool ventilation and treatment methods. These act as significant obstacles to providing a better and healthier recreation space.

It is important to acknowledge that chemical treatment itself is not inherently harmful. Chlorination and other sanitation methods have been critical in preventing waterborne illnesses, controlling microbial growth, and making pool use widely accessible and safe. The challenge lies not in eliminating these treatments but in optimizing their use in order to find ways to strike a balance between disinfection efficacy and user safety.

The ongoing risks posed by harmful disinfection byproducts demand more attention from both public health authorities and the general public. Indoor pools are intended to be spaces of recreation and physical activity, but without addressing the chemical dangers that lie in the water and the air, they potentially contribute to long-term harm. Advancing treatment technology and investing in research are essential steps to ensure these facilities remain safe for everyone.

REFERENCES

- 23 Gassed While Swimming. (1965, July 15). *The New York Times*, 15.
- Abilleira, E., Goñi-Irigoyen, F., Aurrekoetxea, J. J., Cortés, M. A., Ayerdi, M., & Ibarluzea, J. (2023). Swimming pool water disinfection by-products profiles and association patterns. *Heliyon*, 9(2). <https://doi.org/10.1016/j.heliyon.2023.e13673>
- Aggazzotti, G., Fantuzzi, G., Tartoni, P. L., & Predieri, G. (1990). Plasma chloroform concentrations in swimmers using indoor swimming pools. *Archives of Environmental Health*, 45(3), 175–179. <https://doi.org/10.1080/00039896.1990.9936712>
- Allen, J. M., Plewa, M. J., Wagner, E. D., Wei, X., Bollar, G. E., Quirk, L. E., Liberatore, H. K., & Richardson, S. D. (2021). Making Swimming Pools Safer: Does Copper–Silver Ionization with Chlorine Lower the Toxicity and Disinfection Byproduct Formation? *Environmental Science &*

- Technology, 55(5), 2908–2918. <https://doi.org/10.1021/acs.est.0c06287>
- Bernard, A., Carbonnelle, S., de Burbure, C., Michel, O., & Nickmilder, M. (2006). Chlorinated pool attendance, atopy, and the risk of asthma during childhood. *Environmental Health Perspectives*, 114(10), 1567–1573. <https://doi.org/10.1289/ehp.8461>
- Boraczyński, M., Balcerek, T., Rożkiewicz, N., Pabiszczak, M., Harasymczuk, M., Sławska, A., & Lutomski, P. (2025). Pulmonary function in swimmers exposed to disinfection by-products: A narrative review. *Frontiers in Physiology*, 15, 1473302. <https://doi.org/10.3389/fphys.2024.1473302>
- Cheema, W. A., Kaarsholm, K. M. S., & Andersen, H. R. (2017). Combined UV treatment and ozonation for the removal of by-product precursors in swimming pool water. *Water Research*, 110, 141–149. <https://doi.org/10.1016/j.watres.2016.12.008>
- Clean Water and Clean Air in Modern Aquatics Facilities – PUPN. (2024, April 22). <https://pupnmag.com/article/clean-water-and-clean-air-in-modern-aquatics-facilities-2/>
- Couto, M., Bernard, A., Delgado, L., Drobnic, F., Kurowski, M., Moreira, A., Rodrigues-Alves, R., Rukhadze, M., Seys, S., Wiszniewska, M., & Quirce, S. (2021a). Health effects of exposure to chlorination by-products in swimming pools. *Allergy*, 76(11), 3257–3275. <https://doi.org/10.1111/all.15014>
- Couto, M., Bernard, A., Delgado, L., Drobnic, F., Kurowski, M., Moreira, A., Rodrigues-Alves, R., Rukhadze, M., Seys, S., Wiszniewska, M., & Quirce, S. (2021b). Health effects of exposure to chlorination by-products in swimming pools. *Allergy*, 76(11), 3257–3275. <https://doi.org/10.1111/all.15014>
- Daiber, E. J., DeMarini, D. M., Ravuri, S. A., Liberatore, H. K., Cuthbertson, A. A., Thompson-Klemish, A., Byer, J. D., Schmid, J. E., Afifi, M. Z., Blatchley, E. R., & Richardson, S. D. (2016). Progressive Increase in Disinfection Byproducts and Mutagenicity from Source to Tap to Swimming Pool and Spa Water: Impact of Human Inputs. *Environmental Science & Technology*, 50(13), 6652–6662. <https://doi.org/10.1021/acs.est.6b00808>
- Dehghani, M., Shahsavani, S., Mohammadpour, A., Jafarian, A., Arjmand, S., Rasekhi, M. A., Dehghani, S., Zaravar, F., Derakhshan, Z., Ferrante, M., & Oliveri Conti, G. (2002). Determination of chloroform concentration and human exposure assessment in the swimming pool. *Environmental Research*, 203, 111883. <https://doi.org/10.1016/j.envres.2021.111883>
- Donat-Vargas, C., Kogevinas, M., Benavente, Y., Costas, L., Campo, E., Castaño-Vinyals, G., Fernandez-Tardon, G., Llorca, J., Gómez-Acebo, I., Aragonés, N., Pollán, M., Casabonne, D., & Villanueva, C. M. (2024). Lifetime exposure to brominated trihalomethanes in drinking water and swimming pool attendance are associated with chronic lymphocytic leukemia: A Multicase-Control Study in Spain (MCC-Spain). *Journal of Exposure Science & Environmental Epidemiology*, 34(1), 47–57. <https://doi.org/10.1038/s41370-023-00600-7>
- Esschert, K. L. V. (2019). Pool Chemical Injuries in Public and Residential Settings—United States, 2008–2017, and New York, 2018. *MMWR. Morbidity and Mortality Weekly Report*, 68. <https://doi.org/10.15585/mmwr.mm6819a2>
- Fernández-Luna, Á., Burillo, P., Felipe, J. L., del Corral, J., García-Unanue, J., & Gallardo, L. (2016). Perceived health problems in swimmers according to the chemical treatment of water in swimming pools. *European Journal of Sport Science*, 16(2), 256–265. <https://doi.org/10.1080/17461391.2014.1001877>
- Hanafi, A. M., Ibrahim, M. A., Abou-deif, T. M., & Morcos, S. M. (2023). Enhancing indoor air quality

-
- and thermal comfort in indoor swimming pool facilities: Investigating the impact of ventilation system configurations. *Journal of Engineering and Applied Science*, 70(1), 114. <https://doi.org/10.1186/s44147-023-00276-8>
- Helenius, I., Rytälä, P., Sarna, S., Lumme, A., Helenius, M., Remes, V., & Haahtela, T. (2002). Effect of continuing or finishing high-level sports on airway inflammation, bronchial hyperresponsiveness, and asthma: A 5-year prospective follow-up study of 42 highly trained swimmers. *Journal of Allergy and Clinical Immunology*, 109(6), 962–968. <https://doi.org/10.1067/mai.2002.124769>
- Jacobs, J. H., Spaan, S., Rooy, G. B. G. J. van, Meliefste, C., Zaat, V. a. C., Rooyackers, J. M., & Heederik, D. (2007). Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. *European Respiratory Journal*, 29(4), 690–698. <https://doi.org/10.1183/09031936.00024706>
- Jarin, M., Ly, J., Goldman, J., & Xie, X. (2025). Water Disinfection Systems for Pools and Spas: Advantages, Disadvantages, and Consumer Views in the US. *ACS ES&T Water*, 5(2), 525–538. <https://doi.org/10.1021/acsestwater.4c00612>
- Kalita, I., Kamilaris, A., Havinga, P., & Reva, I. (2024). Assessing the Health Impact of Disinfection Byproducts in Drinking Water. *ACS ES&T Water*, 4(4), 1564–1578. <https://doi.org/10.1021/acsestwater.3c00664>
- Lee, L. T., & Blatchley, E. R. (2022). Long-Term Monitoring of Water and Air Quality at an Indoor Pool Facility during Modifications of Water Treatment. *Water*, 14(3), Article 3. <https://doi.org/10.3390/w14030335>
- Mohamed, H. M., Sadeq, A. M., Sleiti, A. K., & Ahmed, S. F. (2023). Thermal Comfort Conditions of an Indoor Hot-Climate Swimming Pool. *Research Square*. <https://doi.org/10.21203/rs.3.rs-3801514/v1>
- Mohamed, H. M., Sadeq, A. M., Sleiti, A. K., & Ahmed, S. F. (2025). Thermal Comfort Assessment of an Indoor Swimming Pool in a Hot Climate: A CFD and HAP Simulation Study. *Indoor Air*, 2025(1), 4502431. <https://doi.org/10.1155/ina/4502431>
- Mplougoura, A., Klona, K., Mavridou, A., & Mandilara, G. D. (2025). An Assessment of Hazards and Associated Risks in Greek Swimming Pools. *Water*, 17(7), Article 7. <https://doi.org/10.3390/w17070929>
- Olsen, K. (2007). Clear waters and a green gas: A history of chlorine as a swimming pool sanitizer in the United States. https://www.researchgate.net/publication/251231217_Clear_waters_and_a_green_gas_a_history_of_chlorine_as_a_swimming_pool_sanitizer_in_the_United_States
- Rojas, G., & Grove-Smith, J. (2018). Improving Ventilation Efficiency for a Highly Energy Efficient Indoor Swimming Pool Using CFD Simulations. *Fluids*, 3(4), Article 4. <https://doi.org/10.3390/fluids3040092>
- Spiliotopoulou, A., Hansen, K. M. S., & Andersen, H. R. (2015). Secondary formation of disinfection by-products by UV treatment of swimming pool water. *Science of The Total Environment*, 520, 96–105. <https://doi.org/10.1016/j.scitotenv.2015.03.044>
- Standards 62.1 & 62.2. (n.d.). Retrieved August 7, 2025, from <https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2>
- Studziński, W., Poćwiardowski, W., & Osińska, W. (2021). Application of the Swimming Pool Backwash Water Recovery System with the Use of Filter Tubes. *Molecules*, 26(21), Article 21. <https://doi.org/10.3390/molecules26216620>

- Tiwari, A., Oliver, D. M., Bivins, A., Sherchan, S. P., & Pitkänen, T. (2021). Bathing Water Quality Monitoring Practices in Europe and the United States. *International Journal of Environmental Research and Public Health*, 18(11), Article 11. <https://doi.org/10.3390/ijerph18115513>
- Wagner, E. D., & Plewa, M. J. (2017). CHO cell cytotoxicity and genotoxicity analyses of disinfection by-products: An updated review. *Journal of Environmental Sciences (China)*, 58, 64–76. <https://doi.org/10.1016/j.jes.2017.04.021>
- Wastensson, G., & Eriksson, K. (2020). Inorganic chloramines: A critical review of the toxicological and epidemiological evidence as a basis for occupational exposure limit setting. *Critical Reviews in Toxicology*, 50(3), 219–271. <https://doi.org/10.1080/10408444.2020.1744514>
- Westerlund, J., Bryngelsson, Ing-Liss, Löfstedt, Håkan, Eriksson, Kåre, Westberg, Håkan, & Graff, P. (2019). Occupational exposure to trichloramine and trihalomethanes: Adverse health effects among personnel in habilitation and rehabilitation swimming pools. *Journal of Occupational and Environmental Hygiene*, 16(1), 78–88. <https://doi.org/10.1080/15459624.2018.1536825>
- Zaccarin, M., Zanni, S., Gallè, F., Protano, C., Valeriani, F., Liguori, G., Romano Spica, V., & Vitali, M. (2022). Studying Respiratory Symptoms Related to Swimming Pools Attendance in Young Athletes: The SPHeRA Study. *Toxics*, 10(12), 759. <https://doi.org/10.3390/toxics10120759>
- Zare Afifi, M., & Blatchley, E. R. (2016). Effects of UV-based treatment on volatile disinfection byproducts in a chlorinated, indoor swimming pool. *Water Research*, 105, 167–177. <https://doi.org/10.1016/j.watres.2016.08.064>
- Zwick, H., Popp, W., Budik, G., Wanke, T., & Rauscher, H. (1990). Increased sensitization to aeroallergens in competitive swimmers. *Lung*, 168(1), 111–115. <https://doi.org/10.1007/BF02719681>