Environmentally sustainable water management in public swimming pools using combined disinfection technologies

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Abstract — **Managing water quality in public swimming pools requires simultaneously ensuring microbiological safety, controlling chemical loading, and efficiently utilizing water and energy resources. Conventional chlorination provides the necessary residual disinfection protection; however, the interaction of chlorine compounds with organic and inorganic water components leads to the formation of disinfection by-products (DBPs). This study analyzes options for the environmentally sustainable management of pool water by combining chemical, physical, and oxidative technologies. A comparative analysis was conducted of chlorination, salt electrolysis, UV irradiation, ozonation, and combinations thereof, alongside an analysis of monitoring data from 1,675 water samples taken from public swimming pools in Sofia between 2019 and 2023. The results reveal significant fluctuations in chemical and microbiological parameters and an absence of strong linear correlation between residual free chlorine and the other parameters studied. The findings underscore the need to manage water quality as a multi-factorial system. An integrated multi-barrier model is proposed, combining effective circulation and filtration, supplementary physical or oxidative treatment, residual disinfection protection, and adaptive monitoring. The potential resource and environmental benefits of specific technological configurations should be quantitatively assessed in future studies.**

Keywords — **disinfection, environmental sustainability, sustainable water management, swimming pools**

1.INTRODUCTION

Public swimming pools are a vital component of the infrastructure for sports, recreation, rehabilitation, and preventive health care. Their intensive use places high demands on water quality and user safety. Pool water constitutes a dynamic system characterized by the continuous interaction of physical, chemical, and biological processes; its quality depends on the water source, bather load, the efficiency of circulation and filtration systems, physicochemical parameters, and the applied disinfection regimen.

Chlorination remains the most widely used method for disinfecting swimming pool water [1]. Its primary technological advantage lies in its ability to provide both immediate disinfection and residual disinfectant protection throughout the water volume. At the same time, chlorination is associated with the formation of disinfection by-products (DBPs) resulting from the interaction between active chlorine species and organic and inorganic precursors present in the water [2], [3]. Numerous DBPs have been identified in pool water, including trihalomethanes, haloacetic acids, haloacetonitriles, and chloramines [4], [5]. Their formation and distribution depend on a range of factors, including the characteristics of the water source, free residual chlorine concentration, organic and nitrogenous loads, temperature, and pH [5], [6]. These interactions demonstrate that managing pool water quality cannot be reduced solely to maintaining a specific disinfectant concentration. It requires the simultaneous management of pollution sources, filtration, circulation, physicochemical balance, the disinfection regime, and operational load dynamics.

Alongside traditional chlorination, technologies such as salt electrolysis, ultraviolet irradiation, and ozonation—as well as various combinations thereof—are employed. Each method possesses distinct mechanisms of action, technical advantages, and limitations; consequently, they can be viewed not as mutually exclusive alternatives, but as functionally complementary elements of an integrated water treatment system.

From an environmental perspective, sustainable management entails achieving sanitary safety while simultaneously accounting for chemical load, the formation of disinfection by-products (DBPs), and the consumption of water and energy resources. The development of energy-efficient filtration technologies and intelligent management systems for pool facilities also reflects a trend toward integrating sanitary and resource-related operational aspects [7], [8].

The aim of this study is to analyze the potential of combined disinfection technologies as a tool for the environmentally sustainable management of water in public swimming pools by integrating microbiological safety, chemical load control, and process optimization.

2. DISINFECTION TECHNOLOGIES AND ENVIRONMENTAL ASPECTS

2.1. Chlorination

Chlorine is widely used for disinfecting swimming pool water due to its effectiveness against a broad spectrum of microorganisms, its relatively easy dosing, and its ability to provide residual protection. Its disinfection efficiency depends on free chlorine concentration, pH, temperature, contact time, and the characteristics of the contamination.

The main limitation relates to reactions between chlorine species and organic precursors in the water. Studies have found significant variability in disinfection by-product (DBP) formation depending on operating conditions and water characteristics [5], [6].

Therefore, the environmental issue should not be framed as a conflict between "chlorine" and "chlorine-free" methods. Residual disinfection performs a specific protective function. From the perspective of sustainable

management, the question is how to integrate the necessary residual protection with other processes to optimize the performance of the entire system.

2.2. Salt electrolysis

In salt electrolysis, the active disinfectant is generated *in situ* via an electrochemical process. An electric current is passed through a saline solution, and the primary oxidant produced is chlorine in the form of hypochlorous acid. Consequently, this technology does not constitute chlorine-free disinfection but rather a different method of generating active chlorine species [9]–[10]. 05-090826

An advantage of the method is the ability to continuously generate the disinfectant, rather than periodically introducing larger quantities of a chlorine-based agent. At the same time, literature data indicate that chlorine-based disinfection by-products (DBPs) continue to form during electrolysis, and toxicity concerns are similar to those associated with conventional chlorine disinfection [9]–[10]. Therefore, salt electrolysis should be viewed as a technological variant of chlorine disinfection rather than a standalone solution to the issue of chemical loading.

2.3. UV irradiation

Ultraviolet irradiation is commonly used as a secondary process in chlorinated pools and is effective for inactivating microorganisms, including pathogens resistant to standard chlorination regimens [11], [12].

A key advantage of UV treatment is that this physical process does not require the addition of a chemical disinfectant. However, UV technology does not provide a residual disinfectant effect within the water volume, which limits its use as a sole barrier in public pools subject to continuous microbiological loading.

The impact of UV on DBPs is complex. Literature data indicate the potential for both the photolytic removal of certain products and the secondary formation of DBPs, depending on the UV dose, water characteristics, and subsequent chemical treatment [13], [14]. Therefore, UV treatment cannot automatically be classified as more environmentally friendly solely based on the physical nature of the process.

2.4. Ozonation

Ozone has a high oxidation potential and can react with various organic and inorganic components in the water. When not directly consumed in reactions with reducing agents, ozone can decompose to form highly reactive hydroxyl radicals; the mechanism and rate of this process depend on pH and the characteristics of the organic matter [15], [16].

Ozonation can alter organic precursors, thereby influencing the subsequent formation of disinfection by-products (DBPs) during chlorination. Lee et al. established a relationship between the disinfection method used and the formation of various DBPs [17]. An experimental study by Hansen et al. demonstrated that the effect of ozonation on trihalomethane (THM) formation is not uniform: a reduction in THM formation potential is observed with certain water types, whereas ozonation of previously chlorinated pool water can lead to increased subsequent formation [18].

Ozone does not provide sustained residual protection. Consequently, ozonation is typically combined with a subsequent residual disinfection step [18].

2.5. Combined technologies

Combining different technologies allows individual stages to perform specific functions. UV irradiation can provide an additional physical barrier, ozone exerts an oxidative effect on specific organic components, and residual free chlorine offers continuous protection throughout the water volume.

Advanced oxidation processes also employ combinations such as O_3/UV, O_3/H_2O_2, and UV/H_2O_2, which stimulate the formation of hydroxyl radicals [19], [20]. However, literature data indicate a need to optimize process parameters, as increasing the oxidative potential does not automatically guarantee a reduction in all disinfection by-products (DBPs) [14].

Consequently, the technological objective shifts from maximizing the effect of a single method to optimizing the interaction between multiple methods.

3. MATERIALS AND METHODS

The empirical part of the study is based on water quality monitoring results from outdoor and indoor public swimming pools in Sofia over the period 2019–2023. A total of 1675 water samples were analyzed: 376 in 2019, 273 in 2020, 146 in 2021, 246 in 2022, and 611 in 2023.

Chemical and microbiological parameters were examined; specifically, for the purposes of this article, the analysis covered residual free chlorine, nitrites, ammonium ions, permanganate oxidizability, *Escherichia coli*, total coliform titer, and enterococcal titer.

Laboratory tests were conducted in accordance with the applicable standardized methods specified in the original study, including BDS EN ISO 7393-2:2018 for the determination of residual free chlorine. The results were organized into annual databases. Python and the pandas library were used for data processing, aggregation, and analysis. Min-Max scaling was applied in some of the comparative analyses.

Z-tests were used to assess the statistical significance of differences at a significance level of $\alpha = 0.05$. Correlation analysis was performed between residual free chlorine and the other chemical and microbiological parameters.

The present study has an important methodological limitation. The monitored pools are not grouped according to the disinfection technology configuration employed. Consequently, the monitoring data cannot be used to directly demonstrate the superiority of any specific combined technology. They do, however, allow for an assessment of whether water quality under actual operating conditions can be adequately characterized by a single disinfection parameter.

4. RESULTS AND DISCUSSION

4.1. Chemical parameters

Of the total number of analyzed cases, 797 (48%) met the chemical requirements, while 878 (52%) did not. For outdoor pools, 60% of the samples met the chemical requirements, whereas for indoor pools, the figure was 48%. The difference between the two groups is statistically significant according to the Z-test for proportions applied

in the baseline study (p = 0.0001).

Residual free chlorine levels fell outside the regulatory range in 555 out of 1,675 records (33%). In this group, the mean value was 0.78 mg/dm³, the standard deviation was 0.58 mg/dm³, the median was 0.84 mg/dm³, and the range was 0 to 3.2 mg/dm³.

Mean annual values for residual free chlorine showed the following trend: 0.69 mg/dm³ in 2019, 0.64 mg/dm³ in 2020, 0.47 mg/dm³ in 2021, 0.56 mg/dm³ in 2022, and 1.04 mg/dm³ in 2023. The baseline study also recorded an increase in permanganate oxidizability in 2023.

The simultaneous variation of these parameters is significant for the interpretation of the results. A higher level of residual free chlorine should not automatically be interpreted as an indicator of lower organic load or better overall water quality.

4.2. Microbiological parameters

Microbiological results also show significant variability. In 2019, over 70% of the tested sites met microbiological requirements, whereas in 2023, this proportion fell below 44%.

Regarding *E. coli*, positive results reached 7.2% in 2023; for the total coliform titer, the figure was 6.8%, and for the enterococcus titer, it was nearly 10%. These results coincide with the increase in the average residual free chlorine level during the same year.

This observation does not prove a causal link between elevated residual chlorine and microbiological non-compliance. It demonstrates that the instantaneous concentration of residual free chlorine is not sufficient on its own to assess the condition and effectiveness of the entire system.

4.3. Correlation analysis

Correlation analysis did not establish a strong linear relationship between residual free chlorine and the other parameters studied. The obtained coefficients are: −0.326 for nitrites, +0.138 for the ammonium ion, +0.019 for permanganate oxidizability, −0.174 for *E. coli*, −0.158 for the coli titer, and −0.024 for the enterococcus titer.

The absence of a strong linear correlation should not be interpreted as evidence of a lack of disinfection effect from free chlorine. Correlation analysis does not determine the minimum required disinfectant concentration, nor does it prove causality. The results indicate that water quality under actual operating conditions is shaped by the combined effect of multiple factors.

This specific result is directly relevant to the technological concept of the present study. Increasing the quantity of a disinfectant cannot substitute for the management of the entire water system.

The data support the need to view residual free chlorine as an important—though not the sole—system parameter, operating in conjunction with the control of organic loading, filtration, circulation, pH, temperature, and microbiological monitoring.

5. INTEGRATED MODEL FOR ENVIRONMENTALLY SUSTAINABLE MANAGEMENT

Comparative technological analysis and monitoring results allow for the management of pool water to be viewed through the concept of multi-barrier protection.

The proposed model comprises the following sequence:

control of pollution sources → effective circulation → filtration → primary treatment → supplementary physical/oxidative technology → residual disinfection protection → continuous monitoring → adaptive adjustment of process parameters.

In this approach, individual technologies perform distinct functions. Effective circulation and filtration reduce the load on subsequent processes. UV irradiation can provide an additional physical disinfection barrier, while ozonation offers an oxidative effect on specific organic components. Residual free chlorine ensures protection within the water volume between treatment cycles.

Automated monitoring is a key component. The proposed design recommends continuous measurement of parameters such as free chlorine, pH, ORP, temperature, and conductivity, as well as the integration of process modules into a unified control system.

Such an approach enables a transition from fixed dosing to adaptive control based on the facility's actual load. Consequently, the operational objective shifts from maintaining a single parameter to ensuring the stability of the entire system.

5.1. Environmental and resource aspects

The environmental assessment of swimming pool technologies should not be based solely on the quantity of chemical substances used. Operating a swimming pool entails the consumption of water and energy for circulation, filtration, heating, and climate control, as well as the generation of backwash and periodic discharge waters.

These processes are considered key factors regarding the resource and environmental impact of pool facilities. Potential measures include optimizing water flows, improving energy efficiency, automation, and utilizing combined technologies with optimized chemical loading.

This allows sustainability to be defined not as a property of a specific method, but as the outcome of the entire technological system's operation:

A system is sustainable if it achieves the required sanitary quality while maintaining an optimal balance between water resources, chemical substances, energy, and technological efficiency.

However, a clear distinction must be made between conceptual potential and empirically proven effects. The current monitoring did not directly measure water consumption, energy consumption, the carbon footprint, or the concentrations of specific disinfection by-products (DBPs). Consequently, the available data do not allow for a quantitative assessment of the environmental efficiency of any specific combined technological configuration.

6. CONCLUSION

Water quality management in public swimming pools cannot be reduced to merely maintaining a specific concentration of a single disinfectant. An analysis of 1,675 water samples from public swimming pools in Sofia between 2019 and 2023 reveals significant fluctuations in chemical and microbiological parameters and confirms the multifactorial nature of the pool water system.

Residual free chlorine plays a vital role in ensuring sustained disinfection protection. However, the results indicate that it should be viewed as part of a broader system encompassing the management of organic load, circulation, filtration, physicochemical parameters, and microbiological control.

A review of the literature shows that different technologies possess distinct functional characteristics. Chlorination provides residual protection but is associated with the formation of disinfection by-products (DBPs). Salt electrolysis offers an alternative method for generating active chlorine species but does not eliminate chlorine-based chemistry. UV irradiation provides a physical disinfection barrier but lacks a residual effect. Ozone possesses high oxidizing potential but also fails to provide sustained protection, and its impact on DBPs depends on specific conditions.

These differences justify the use of integrated multi-barrier systems, in which individual technological processes are viewed not as competing, but as mutually complementary elements. From an environmental perspective, the key conclusion is that sustainability should not be defined by the choice of a single "eco-friendly" technology. Rather, it stems from the optimization of the entire system—encompassing chemical loading, water resources, energy, filtration, circulation, wastewater management, and process monitoring.

The scientific and practical contribution of this study lies in substantiating an integrated model for the environmentally sustainable management of pool water, wherein sanitary safety, chemical loading, and resource efficiency are treated as interconnected components of a unified technological system. Findings from five years of monitoring support the need for a multifactorial management approach, while the literature review identifies combined technologies as a promising tool for its implementation.

A limitation of this study is the absence of direct measurements regarding water consumption, energy usage, concentrations of specific disinfection by-products (DBPs), and carbon footprint across various technological configurations. Consequently, the quantitative assessment of the environmental benefits of specific combined systems should be the subject of future experimental research. The study itself identifies the comparative analysis of energy and carbon footprints, as well as life-cycle assessment, as promising avenues for future work.

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