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Ultraviolet technology application in urban water supply and wastewater treatment in China: Issues, challenges and future directions

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ABSTRACT

This study thoroughly explores the application of Ultraviolet (UV) water treatment technology in urban wastewater treatment and water supply in China, highlighting its crucial role in enhancing water quality safety. UV technology, with its environmentally friendly and low-carbon characteristics, is deemed more in line with the demands of sustainable development compared to traditional chemical disinfection methods. The widespread application of UV technology in urban wastewater treatment in China, particularly in the context of urban sewage treatment, is examined. However, to better promote and apply UV technology, there is a need to deepen the understanding of this technology and its application among a broad base of users and design units. The importance of gaining in-depth knowledge about the performance of UV water treatment equipment, the design calculation basis, and operational considerations, as well as the ongoing development of relevant standards, is underscored to ensure that the equipment used in projects complies with engineering design and production requirements. Furthermore, the positive trend of UV technology in the field of advanced oxidation, indicating a promising trajectory for engineering applications, is pointed out. Regarding the prospects of industrial development, a thorough analysis is conducted in the article, emphasizing the necessity for all stakeholders to collaborate and adopt a multi-level approach to promote the sustainable development and application of UV water treatment technology. This collaborative effort is crucial for providing effective safeguards for China's environment, ecology, and human health.

1. Introduction

In the past few decades, the global threat to water security has steadily increased, particularly in developing countries such as China (Hatami, 2013). Ultraviolet (UV) technology, as an efficient water treatment method, holds significant implications for human health and ecological safety. Numerous studies have demonstrated the efficacy of UV in the inactivation of a wide range of pathogens, bacteria, and viruses transmitted through drinking water, particularly spore-forming parasites and Giardia lamblia (Hijnen et al., 2006; Yang et al., 2020). Since the outbreak of the SARS epidemic in 2003, Ultraviolet (UV) disinfection technology has experienced rapid and widespread implementation in urban wastewater treatment in China. As understanding of UV disinfection deepened, its application expanded to the urban water supply treatment domain as a physical disinfection method (Li et al., 2014; 2018). In comparison to traditional methods, UV disinfection presents notable advantages, including broad-spectrum germicidal properties, absence of chemical agents, prevention of disinfection by-products, and efficacy against antibiotic-resistant pathogenic microorganisms (Ke et al., 2024; Song et al., 2016; Sun et al., 2023). These advantages have played a pivotal role in its gradual adoption. This shift highlights the increasing importance of UV disinfection technology in China's water supply sector. The ability of UV disinfection to improve the safety of water supplies compared to traditional methods recognizes the growing role of this technology in meeting the evolving needs of water treatment and water supply systems in China (Ao et al., 2020). In recent years, research on advanced oxidation processes based on UV (UV-AOPs) has become more profound, with the mature implementation

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of the UV/H_2O_2 technology in engineering applications in China (Song et al., 2021).

Traditional disinfection methods, such as chlorination, have long been the cornerstone of water treatment practices due to their effectiveness in pathogen inactivation. However, these methods come with significant concerns, including the formation of harmful disinfection by-products (DBPs) and the increasing incidence of microbial resistance. In contrast, UV disinfection presents a compelling alternative, offering broad-spectrum efficacy against a wide range of pathogens, including those resistant to chemical treatments, without generating DBPs. This characteristic is particularly crucial in the context of China's water treatment, where the quality and safety of water are paramount amidst diverse environmental challenges. With the advancement of technology application, relevant regulatory authorities have issued a series of laws and regulations regarding UV to ensure standardized management. The substantial contribution of UV technology to public health safety in China cannot be overlooked (Sun et al., 2019). However, despite this, fundamental research on UV disinfection technology and UV-AOPs remains insufficient. Misunderstandings regarding mechanisms and characteristics have led to some challenges in engineering applications that urgently need resolution, posing significant challenges to the development of UV technology.

Combined with literature research and application examples, this study analyzes and summarizes the current status and problems of UV disinfection technology in China's urban water treatment and water supply, and looks forward to the further application of UV-AOPs as a new technology. In addition, this study summarizes the application trend and development direction of UV technology in China's water treatment, which provides feasible strategies for the in-depth application of its future directions.

2. UV technology applications in wastewater disinfection

According to the data provided by National Bureau of Statistics of the People's Republic of China and relevant enterprises, as of 2022, China has completed the construction of 4837 urban wastewater treatment plants with a total processing capacity of 258 million cubic meters per day (National Bureau of Statistics of the People's Republic of China, 2022). A significant proportion of these wastewater treatment plants, built in the past two decades, have adopted UV disinfection technology. Consequently, over half of China's urban population benefits from this water treatment method, leading to a substantial reduction in the use of chlorine-based disinfectants. From the SARS virus outbreak in 2003 to the recent COVID-19, UV technology has proven highly effective in inactivating these viruses (Blatchley Iii et al., 2021). The widespread implementation of UV technology in wastewater treatment plants has effectively controlled the spread of viruses in water.

However, there has been a persistent lack of awareness in China regarding the application of UV disinfection technology in wastewater treatment over an extended period. A notable illustration of this is the presence of demand-consumption barriers between wastewater treatment plants and equipment manufacturers. Many users at wastewater treatment plants mistakenly perceive UV disinfection as a simple procedure involving the placement of UV lamps into water. Additionally, there is a widespread misconception that different UV devices exhibit minimal variations in disinfection efficacy (Sun et al., 2019). These users lack the capability to assess how UV disinfection equipment and its design align with the engineering disinfection requirements. Consequently, they tend to uncritically accept recommendations from equipment manufacturers, often basing decisions solely on pricing, resulting in the mismatch of UV equipment with treatment scale and processes. This, in turn, leads to non-compliant effluents from wastewater treatment plants. Such practices have cast a detrimental impact on the scientific validity and practical effectiveness of UV disinfection technology.

2.1. What restricts UV application effectiveness?

2.1.1. Low quality or poor maintenance of UV sensor

High-quality UV sensors are crucial in the UV disinfection process, ensuring both the effectiveness and efficiency of water treatment. These sensors enable real-time monitoring and adjustment of the UV dose according to varying water quality and flow rates, essential for maintaining operational efficiency and safeguarding public health. The accurate feedback provided by UV sensors on UV intensity and transmittance allows the system to dynamically adapt the UV dose, optimizing energy use while ensuring effective pathogen inactivation. However, the efficacy of UV disinfection systems is heavily dependent on the quality and maintenance of these sensors. Low-quality or improperly maintained sensors can lead to inaccurate UV dose applications, risking insufficient disinfection or unnecessary energy consumption. The absence of reliable sensors restricts the system's ability to adjust to changes in water quality, such as increased turbidity, compromising the safety and efficiency of the water treatment process. Therefore, incorporating high-quality, well-maintained UV sensors is indispensable for achieving the objectives of water treatment safety and operational efficiency, underlining their critical role in the successful application of UV disinfection technology.

2.1.2. Insufficient dosage of equipment

In wastewater treatment plants, a significant reason for the failure to meet effluent standards after UV disinfection is the insufficient irradiation dose provided by UV reactor, which falls short of achieving the disinfection objectives. This may be attributed to a lack of specialized knowledge in UV dose calculation by equipment manufacturers, inadequate testing of UV dose on the equipment, or the intentional setting of doses below the required levels to reduce equipment costs. It could also be a result of wastewater treatment plant users not fully considering the actual operating conditions of the plant when procuring reactor or neglecting the impact of water quality on UV dose and reactor scale, leading to the failure to achieve the specified treatment outcomes(Pullerits, Ahlinder et al. 2020). Turbidity's impact on UV dose is a pivotal concern in ensuring adequate disinfection. Suspended particles in turbid water hinder UV light's ability to penetrate and effectively neutralize pathogens, necessitating increased UV doses for proper treatment. This scenario often results in an insufficient dosage by standard equipment, unable to compensate for the reduced UV transmittance. Additionally, issues with the water level controller may result in inappropriate open-channel water levels, causing disinfection short-circuits and subsequently leading to non-compliant effluent (Linden et al., 2019). The calculation and methodology of UV dose are pivotal concerns in UV disinfection since it serves as the sole parameter for evaluating the compliance of UV reactor and solutions, closely intertwined with equipment scale and costs.

2.1.3. Lack of reliable cleaning system

Inadequate maintenance of the UV lamp sleeves is a significant factor influencing the effluent quality in wastewater treatment plants (Li et al., 2014). Due to the poor quality of wastewater, cleaning the UV lamp sleeves is a crucial daily maintenance task to ensure the equipment meets standards. Although most UV disinfection devices on the market are equipped with online automatic cleaning systems, there are differences in the principles and effectiveness of cleaning. Even with highly efficient mechanical and chemical online automatic cleaning methods, if plant operators forget to replenish the cleaning solution, the online cleaning system may fail to operate properly, leading to scaling on the sleeves and impacting disinfection effectiveness. Some wastewater treatment plants use UV disinfection equipment with online automatic cleaning systems, but the efficiency of these systems in cleaning the sleeve surfaces is inherently low, resulting in suboptimal cleaning outcomes and ultimately leading to equipment abandonment due to difficulties in maintenance and compliance (Li et al., 2018).

Additionally, some wastewater treatment plants choose an inappropriate type of UV lamp technology, rendering the equipment unusable and non-compliant. For instance, medium-pressure UV lamp technology is unsuitable for wastewater treatment, as the high power and operating temperatures of individual lamp tubes can cause certain components in the wastewater to form hard-to-clean deposits on the lamp sleeve, affecting the compliance and maintenance of the equipment.

2.1.4. Continued use of lamps beyond their lifespan

The operation life of UV lamps is crucial, as their aging directly impacts the stable operation of the equipment. Standards stipulate that the operation life of low-pressure lamps is generally between 8000 and 10,000 h, while medium-pressure lamps have a operation life of 4000–8000 h (Liu, 2011). The operation life of new LED lamps is expected to be even longer (Song et al., 2016). The key point in the operation life of UV lamps refers to the moment when the output power of the UV lamp decreases to a level below the minimum required for disinfection equipment, and this is closely related to the aging factor of the UV lamp (Standardization Administration of China, 2015a). In some wastewater treatment plants, to save operational costs, UV lamps that have surpassed their recommended operation life are still used even when the UV output energy has attenuated to a level insufficient for disinfection. This practice results in non-compliant water quality. Additionally, some users, aiming to cut costs, replace only a portion of the old lamps with new ones when the lamp operation life expires, impacting the effluent water quality.

2.1.5. Non-Standard sampling and testing

E. coli exhibits exponential growth at room temperature, particularly in environments with warmth and ample light (Morcinek-Orłowska et al., 2023). Rigorous adherence to established standards is essential for the sampling, storage, transportation, and analysis of microbial water samples from wastewater treatment plant effluents. For instance, promptly collected samples should be stored in a portable dark box containing ice packs and expeditiously transported to the laboratory for processing and analysis. In cases where immediate analysis is not feasible, samples should be refrigerated (Ma et al., 2023). In certain wastewater treatment plant laboratories, improper handling by analysts during the cultivation and testing processes for E. coli can result in erroneous assessments of the compliance of ultraviolet disinfection. Simultaneously, improper procedures by local environmental regulatory agencies during sampling, storage, and subsequent processing and analysis may also lead to misjudgments.

The scarcity of skilled maintenance personnel and specialists for accurate sampling and testing significantly hampers the effectiveness of UV disinfection applications in China. This shortage compromises system reliability and the accuracy of water quality assessments, essential for public health. Without proficient operators, the full potential of UV technology to neutralize pathogens efficiently is not realized, underscoring the critical need for targeted training programs. Addressing this gap is imperative to enhance the operational effectiveness and reliability of UV disinfection in water treatment processes.

2.2. How to judge UV equipment validation?

To address the issues mentioned in the application of UV reactors in wastewater treatment projects, the Chinese urban sewage treatment industry should enhance its understanding and awareness of UV disinfection technology. This involves establishing an integrated UV disinfection application system that incorporates users, manufacturers, and third-party verification platforms (Standardization Administration of China, 2015a). Users and design units should be able to assess whether the UV disinfection equipment and proposed solutions provided by manufacturers meet the engineering design requirements. Actively seeking third-party verification is crucial to safeguarding their interests and public safety.

2.2.1. Bioassay dose

The key to determining whether the UV disinfection equipment scheme from manufacturers aligns with engineering design requirements lies in assessing the UV energy irradiated onto microorganisms, specifically if the UV dose meets the design requirements for disinfection goals. Various methods exist for calculating UV dose (Sun et al., 2019), with the bioassay dose method being the sole approach widely recognized and accepted by regulatory agencies and standard-setting bodies in China and other countries. This method involves measuring changes in microbial concentration before and after treatment by UV reactor, determining the microbial inactivation rate curves under specific conditions such as flow rate, UV transmittance, and light intensity (Standardization Administration of China, 2015a). By adjusting test conditions (typically the flow rate and water quality the equipment processes), UV dose curves for the equipment under different conditions can be obtained, as illustrated in Fig. 1.

The horizontal axis of this curve typically represents the flow rate treated by a single piece of equipment (common in pipe-type UV equipment) or averaged per lamp (common in open channel UV equipment), and the vertical axis is the effective UV dose that can be achieved, i.e., the bioassay dose, with UVT being the UV transmittance of the treated water. Manufacturers should use these equipment curves to calculate the UV dose of their equipment schemes, ultimately reflected in the scale of the equipment in the scheme (number of units, number of lamps, and total installed power of the lamps in the equipment). The higher the dose, the larger the scale of the equipment. Users and design units need only ask the manufacturer for the bioassay dose report and dose curve of the UV disinfection equipment to quickly and easily verify whether the reported equipment scheme meets the disinfection target requirements. To ensure public safety, regulatory and standard-setting authorities worldwide generally require bioassay dose testing of equipment to be conducted by recognized, qualified, or authoritative independent third parties according to relevant industry standards (Linden et al., 2019).

Major verification systems and standards worldwide include the U.S. EPA's validation of drinking water UV disinfection equipment (Blatchley III et al., 2008), Germany's DVGW validation, Austria's ÖNORM validation, and China's national standard "Ultraviolet Water Disinfection Equipment Ultraviolet Dose Testing Methods." (Standardization Administration of China, 2015a). In China, Tsinghua Suzhou Institute of Environmental Innovation and Shandong Province Urban Water Supply and Drainage Water Quality Monitoring Center have established related testing capabilities, but many UV equipment manufacturers have not conducted such tests. Therefore, if users want to buy qualified UV disinfection equipment, they should ask UV equipment manufacturers to

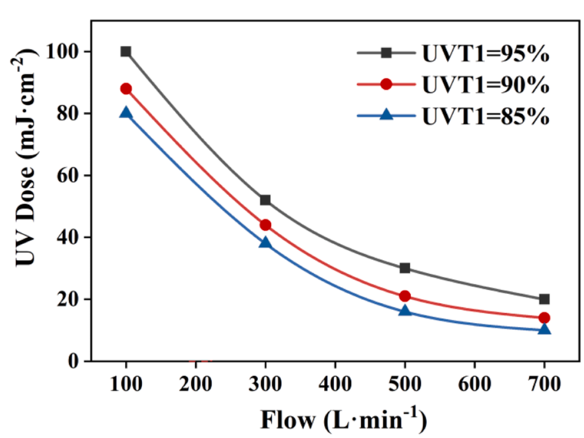

Fig. 1. Bioassay Dosage Curve of UV Device.

provide bioassay dose reports and dose curves obtained by qualified or experienced independent third parties using the manufacturers' disinfection equipment tested according to industry standards (Li et al., 2013). Without such reports, it is difficult to ensure the dose of the manufacturer's equipment.

2.2.2. Reduction equivalent dose (RED)

Reduction Equivalent Dose (RED) concept represents a significant advancement in the standardization and optimization of UV disinfection practices in China's water treatment sector. RED, distinct from the commonly referenced bioassay dose, offers a nuanced approach to evaluating UV disinfection effectiveness by incorporating the specific UV transmittance (UVT) conditions of the treated water, thus enabling a more precise determination of the necessary UV dose for achieving targeted pathogen reduction levels.

While bioassay doses provide a general measure of the UV irradiation required for disinfection, they often do not account for the varying optical properties of different water sources. This limitation is particularly relevant in China, where diverse geographical and industrial factors contribute to significant variations in water quality across regions. The RED approach addresses this variability by ensuring that the UV dose calculations are directly relevant to the specific UVT of the water being treated, thereby enhancing the accuracy and efficiency of UV disinfection systems.

2.2.3. Total installed power and duration of disinfection standard assurance

If users and design units are uncertain about the authenticity and accuracy of the manufacturer's bioassay dose report, they can infer from the total installed power of lamps in the manufacturer's equipment scheme. Under the same type of lamps and disinfectant configuration, if the doses in the UV disinfection equipment schemes from various manufacturers are the same or similar, then the total power of lamps in their schemes should not differ significantly. If a manufacturer's reported equipment scheme has a lamp power 20 % or more lower than that of the industry's best equipment, it can be assumed that the manufacturer's disinfection dose cannot meet the requirements. Although the power of UV disinfection equipment can serve as a reference, it is not entirely recommended for assessing the disinfection performance of UV disinfection equipment (Chen et al., 2011). This is because each manufacturer's equipment system efficiency is different. Some manufacturers with more advanced technology have higher system efficiency, achieving the same disinfection effect with less UV lamp installed power and energy consumption. In fact, even if two UV equipment manufacturers use the same lamps, their disinfection effects can be completely different, even significantly so. On the basis of the same dose, comparing and evaluating the prices, operating costs (including electricity consumption and lamp replacement costs), and operational convenience of equipment from different manufacturers is essential to ensure that users purchase UV disinfection equipment that is both reliable in disinfection performance and cost-effective. From the perspective of protecting user interests, the disinfection performance assurance of UV disinfection equipment should be valid for the entire life cycle of the equipment. This is also something users should pay attention to when choosing equipment from UV equipment manufacturers.

2.2.4. Lamp ageing standards

Lamp ageing is a critical factor influencing the performance and reliability of UV disinfection systems, necessitating adherence to rigorous standards to ensure consistent water treatment efficacy. As UV lamps age, their output intensity decreases, directly impacting the UV dose delivered to the water and, consequently, the effectiveness of the disinfection process. Recognizing and addressing lamp ageing is particularly important in the context of China's growing reliance on UV technology for water treatment, where ensuring the consistent quality of treated water is paramount. International standards, including those by the USEPA, ÖNORM, and DVGW, provide guidelines for compensating for lamp ageing within UV disinfection systems. These standards typically recommend designing systems to deliver the required UV dose assuming a certain percentage of the lamp's initial output—often around 80 %—to account for the decrease in intensity over time. This approach ensures that even at the end of a lamp's operational lifespan, the system can still meet the necessary disinfection criteria.

By incorporating specific criteria for lamp aging into the equipment validation process, operators and regulatory bodies can make informed judgments about the suitability of UV disinfection systems for their intended applications. This includes evaluating whether the system design adequately compensates for decreased lamp efficiency over time, ensuring consistent disinfection performance. Lamp aging standards thus serve as a critical benchmark in the equipment validation process, helping to ensure that UV disinfection systems remain effective throughout their service life, providing a reliable means of protecting public health and the environment from waterborne pathogens.

2.3. Relevant standards in China

With the development of UV disinfection technology in China, corresponding national standards are continuously updated. The formulation and release of these standards aim to better address the aforementioned issues and provide clear methodological guidance for the validation of UV equipment. The process of developing and refining these standards in China involves a rigorous assessment of international best practices, coupled with extensive local research and pilot testing to ascertain their applicability and effectiveness within Chinese water treatment systems. While international standards like those from the USEPA, ÖNORM, and DVGW provide comprehensive guidelines on UV dose requirements, system validation, and operational protocols aimed at ensuring effective pathogen inactivation, China is developing its standards to address specific local challenges. These challenges include variations in water quality, such as higher turbidity levels and unique microbial profiles, necessitating adjustments in UV dose requirements to ensure efficacy within the Chinese environmental context. Furthermore, China's approach to system validation and equipment certification incorporates international methodologies while introducing criteria tailored to the operational and environmental nuances encountered across its diverse landscapes. Operational protocols in China emphasize maintenance and monitoring with a focus on scalability and cost-effectiveness, facilitating broad adoption across both urban and rural settings. By integrating its UV disinfection standards more closely with national water safety regulations, China aims not only to align with international safety benchmarks but also to provide flexible, effective implementation across its varied water treatment infrastructure. This tailored approach underscores China's commitment to leveraging UV disinfection technology for enhanced water safety and public health, acknowledging the importance of customizing global standards to fit local realities.

In 2005, China issued the "Ultraviolet(UV) disinfection equipment for municipal water and wastewater treatment" standard (GB/T 19,837—2005), standardizing the classification, technical requirements, inspection rules, labeling, packaging, transportation, and storage of urban water supply and drainage UV disinfection equipment (Standardization Administration of China, 2005). According to this standard, the UV biological verification dose for drinking water disinfection should not be less than 40 mJ/cm^2. The publication of this standard promoted the advancement of UV disinfection technology and regulated the UV disinfection equipment market. In 2019, the standard was replaced by the new one (GB/T 19,837—2019), which revised the testing methods for UV lamp life, aging coefficient, and sleeve fouling coefficient, providing more comprehensive scientific basis for manufacturers, design units, and users in the production and use of UV disinfection equipment (Standardization Administration of China, 2019). Prior to this, China also released the "Ultraviolet equipment for water disinfection—Ultraviolet dose testing method" (GB/T 32, 091—2015) and "Ferms of ultraviolet disinfection technology" (GB/T 32,092—2015). These standards explain the dose testing of UV equipment and use biological verification to test the disinfection effectiveness of UV reactors (X. Standardization Administration of China, 2015a; X. 2015b). Initially, quasi-parallel light beam instruments were used to characterize the UV dose response of target microorganisms, as shown in Fig. 2.

In 2020, the "Hygienic requirements for ultraviolet appliance of disinfection" (GB 28,235—2020) replaced the "Safety and sanitary standard for ultraviolet appliance for air disinfection" (GB 28,235—2011) and comprehensively implemented the newly added requirements for UV water disinfectors, aligning more with technological developments and market applications (Standardization Administration of China, 2020, 2011).

3. UV technology applications in drinking water disinfection

3.1. Why should UV disinfection be used?

With economic development and improvement in living standards, there is an increasing concern among the government and the public regarding the safety of drinking water. In recent years, China's drinking water quality standards have undergone multiple revisions, with the latest "Standards for drinking water quality" (GB 5749—2022) imposing higher safety requirements, especially concerning disinfection by-products and residual chlorine limits, posing challenges to traditional chlorine disinfection processes (Standardization Administration of China, 2022). UV disinfection, as a physical method, has emerged as a crucial choice to enhance water supply safety under these new conditions due to its broad-spectrum bactericidal properties, non-use of chemical agents, and absence of disinfection by-product generation (Li et al., 2021).

Chlorine-resistant microorganisms are present in drinking water, including well-known chlorine-resistant microorganisms like Giardia lamblia and Cryptosporidium (Liu et al., 2020). Additionally, research indicates the common occurrence of chlorine-resistant microorganisms such as Mycobacterium avium, Pseudomonas aeruginosa, Bacillus cereus, Legionella, and sulfur-oxidizing bacteria in the effluent water of water plants and water supply networks in China, some of which are opportunistic pathogens (Jing et al., 2022; Liu et al., 2008; Zhang et al., 2015). Effectively inactivating these chlorine-resistant microorganisms requires a significant increase in the chlorine's CT value, rendering chlorine disinfection economically unfeasible or even impossible on a large scale and greatly increasing the risk of exceeding disinfection by-product limits. Strictly speaking, the traditional single chlorine disinfection unit model has safety loopholes, and in the event of a chlorine disinfection unit failure, the water plant completely loses its microbial safety barrier (Pan et al., 2023). Therefore, from both biological and chemical safety perspectives, a multi-barrier disinfection strategy and concept become essential for improving water supply safety. This concept is widely accepted and practiced in urban water plants in North America and the European Union, and UV disinfection, meeting both biological and chemical safety requirements, becomes an indispensable, even crucial, part of the combined disinfection method.

3.2. Application issues of UV disinfection in water supply

In recent years, the concept of multi-barrier disinfection and UV disinfection technology has gradually gained recognition and promotion in China's water supply treatment. Among them, the third phase of the Tianjin TEDA Water Plant built in 2009 and the UV disinfection process at the Shanghai Linjiang Water Plant became the earliest water plants in China to operate UV as the main disinfection process. The UV-chlorine combined disinfection process of the Beijing Guogongzhuang Water Plant, commissioned in 2014, became a demonstration project of the "Twelfth Five-Year" national key project. The UV disinfection process of the Lhasa Najin Water Plant, built in 2017, is the largest scale application of domestic equipment. Practice shows that UV disinfection as the main disinfection process can improve the microbial safety of water quality, reduce the CT value of subsequent chlorine disinfection processes to some extent, and reduce the generation of disinfection by-products and the toxic effects of water, playing a positive role in ensuring water quality safety. Moreover, research has found that combining UV and chloramine is more effective than using UV or chloramine alone, significantly reducing disinfection by-products, lowering genetic toxicity, and enhancing the disinfection efficacy against both protozoa and chlorine-resistant pathogenic bacteria (Sun et al., 2019). Combined with chlorine disinfection, compared to traditional UV disinfection, improves the safety of water quality in the network (Ao et al., 2020).

In actual application, compared to wastewater plant users, water

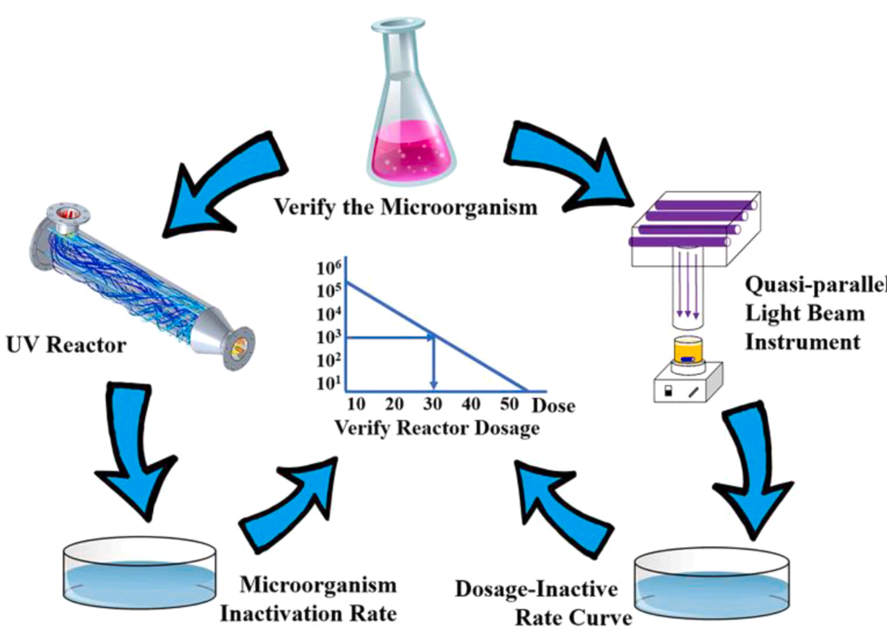

Fig. 2. Dosage Verification of UV Disinfection Reactor.

supply plant users pay more attention to the disinfection performance and quality of UV disinfection equipment, which is necessary to ensure water supply safety. In the selection and procurement of UV disinfection equipment, apart from the mandatory industry-standard bioassay dose verification, China's water-related approvals are also an important certification requirement to consider. In some cities, local health and quarantine departments explicitly require water supply plants to use water-related equipment and materials with domestic water-related approvals before they can be put into production and supply water. It is understood that more and more cities are considering or designing drinking water UV disinfection processes. It can be foreseen that UV disinfection will play a more important role in improving the safety of urban water supply quality in China.

4. UV technology applications in AOPs

In addition to disinfecting water, ultraviolet (UV) light can also be used in advanced oxidation processes to generate hydroxyl radicals or other reactive radicals by photolysis in combination with hydrogen peroxide or other oxidants (Ao et al., 2023; X. 2018; Miklos et al., 2018). These hydroxyl radicals are strong oxidants without selectivity, and compared to ozone, they have a broader spectrum in treating chemical pollutants with a lower risk of producing by-products like bromates (Miklos et al., 2018). Therefore, they can effectively degrade a wider range of organic pollutants in water, including N—Nitrosodimethylamine (NDMA), which has garnered widespread attention and discussion in the field of water supply. NDMA is a common target pollutant in foreign water treatment and reclaimed water treatment standards, and UV advanced oxidation technology is currently considered the most economically effective method and engineering approach for treating NDMA (Szczuka et al., 2020). Additionally, UV advanced oxidation technology achieves a removal rate of up to 90 % for 2-Methylisoborneol (2-MIB) and geosmin in water, and can remove over 99 % of various algal toxins (Tan et al., 2016). Therefore, it is considered an effective technical option for controlling odor and related algal toxins in drinking water, especially in its application for seasonal intermittent operation modes.

In foreign drinking water and related reclaimed water treatment, UV advanced oxidation technology has many successful engineering cases. In China, its application is still in the nascent stage. The Qingyun Shuanglonghu Drinking Water Treatment Plant in Dezhou, Shandong was completed in 2020, which is the first case in China to apply advanced ultraviolet oxidation technology to water plants. With increasing awareness and attention to emerging pollutants in water bodies, and as the treatment of pollutants in urban water supply in China evolves towards trace and ultra-trace levels, UV advanced oxidation technology will play an important role in the treatment of urban drinking water, especially in high-quality drinking water.

5. Challenges and future directions

The application of ultraviolet (UV) water treatment technology in Chinese urban water supply and wastewater treatment plants has driven relevant research in domestic research institutions and higher education. These studies contribute to the understanding and mastery of the application areas of this technology. Fig. 3 illustrates the publication trend of literature on the theme of "UV disinfection" in the Scopus database with China as the source. It is evident that there is a fluctuating growth in literature publication around 2003, corresponding to the practical scenario. This period not only laid the technical foundation for the use of UV disinfection technology in urban wastewater treatment plants during and after the SARS epidemic in 2003 but also supported its subsequent development. Analysis of domestic literature on UV disinfection technology indicates that these publications cover various aspects, including the UV disinfection inactivation mechanism, sterilization effects, UV disinfection reactor design, dose verification, UV intensity monitoring, engineering applications, and operational performance and cost analysis of UV disinfection equipment used in projects. These publications provide substantial support for a comprehensive understanding of UV water treatment technology among a wide range of users and design units. This literature provides support for a broad range of users and design units to understand and recognize UV water treatment technology. However, research on UV water treatment technology in China exists in a state of "each fighting their own battle," with a lack of sufficient peer exchange, possibly due to the lack of a professional exchange platform in this field domestically. To address this, Tsinghua University led the establishment of the Ultraviolet Committee of the China Association of Environmental Protection Machinery, increasing domestic and international industry exchanges through activities such as signing a memorandum of cooperation with the International Ultraviolet Association (IUVA) and organizing international symposiums on UV technology. These efforts will greatly benefit the enhancement of China's UV water treatment technology level and influence.

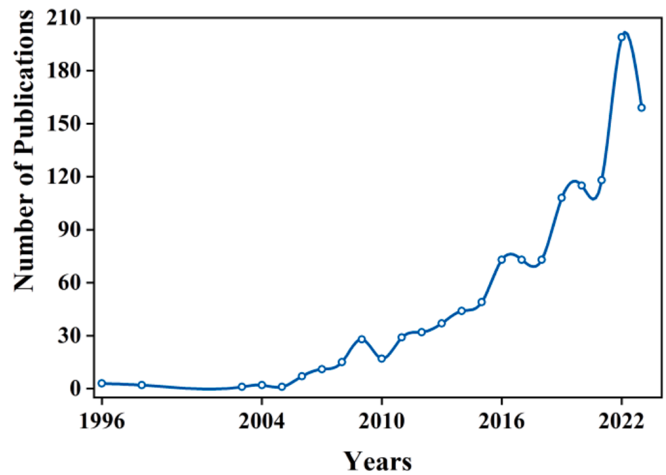

Fig. 3. Number of Annual Publication during 1996–2023 on Scopus by searching key words of "Ultraviolet disinfection" and located in China.

From a research perspective, further scientific exploration is essential for the future development of UV technology in water treatment. It is crucial to advance various technologies from laboratory-scale to pilot-scale, especially focusing on novel UV-AOPs systems, UV light-emitting diodes (UVLED), excimer lamps, and other emerging UV light sources. The emphasis should be on the research of these new technologies for the next generation of intelligent, energy-efficient UV water treatment systems, with a particular focus on their practical engineering applications. Simultaneously, there is a need for innovative system designs for UV disinfection equipment and water supply networks, considering the overall compatibility of technology and equipment. Updating regulations governing the application of UV technology in wastewater and drinking water, and conducting a comprehensive assessment of potential operational issues under complex conditions, requires collaborative efforts from the scientific community, industry, and regulatory authorities.

6. Conclusions

Ultraviolet (UV) water treatment technology is an environmentally, ecologically, and human-friendly technology. Compared to chemical disinfection methods, it is more low-carbon and holds significant value for the sustainable development of human society. This technology has already been widely applied in urban wastewater treatment in China and will also play a significant role in enhancing the safety of water supply quality in the future. However, there is still a need to improve the understanding and mastery of UV technology and its applications in China, especially among the broad base of users and design units. It is crucial for them to fully understand the design and calculation basis of the performance of UV water treatment equipment and the main issues to be aware of during operation, ensuring that the relevant equipment used in projects meets the engineering design and production requirements.

In refining UV disinfection standards to suit China's diverse environmental and operational landscapes, the collaboration among stakeholders is pivotal. Regulatory bodies bear the responsibility of establishing and updating guidelines that reflect both international best practices and local necessities, ensuring standards are both rigorous and applicable. Researchers and academics play a critical role in advancing our understanding of UV technology's effectiveness across China's varied water conditions, contributing to the development of more adaptable and efficient disinfection solutions. Industry participants, including equipment manufacturers and water treatment operators, must commit to implementing these standards, ensuring their systems are both compliant and optimized for performance over time. This collaboration extends to ongoing training and education to keep pace with technological advancements and regulatory changes. The synergy between these stakeholders is fundamental to the successful deployment of UV disinfection technology in China, enhancing water safety and public health through a unified approach that melds scientific innovation with practical application and regulatory oversight. This collective effort underscores the importance of cooperation in advancing water treatment technologies to meet the challenges of ensuring safe, clean water across China.

CRediT authorship contribution statement

Wenjun Sun: Writing – review & editing, Validation, Supervision, Project administration, Formal analysis, Conceptualization. **Xiuwei Ao:** Writing – original draft, Investigation, Data curation, Conceptualization. **Dongming Lu:** Visualization, Resources, Methodology. **Yuanna Zhang:** Project administration, Data curation. **Yanei Xue:** Validation, Resources, Methodology, Investigation. **Siyuan He:** Software, Methodology, Investigation, Data curation. **Xi Zhang:** Methodology, Investigation, Data curation. **Ted Mao:** Writing – review & editing, Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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