

Short Review: Application Of UV LED Light And Ozone As A Water Sterilization Method Against E. Coli

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ABSTRACT

This review investigates the effectiveness of ultraviolet light-emitting diodes (UV-LEDs) and ozone as water sterilization methods for the inactivation of *Escherichia coli* (*E. coli*), a widely recognized indicator of fecal contamination and waterborne pathogens. The objective is to evaluate their disinfection efficiency, operational feasibility, and sustainability compared to conventional approaches. A systematic search of recent experimental and review articles (2018–2024) was conducted through databases such as Scopus and Google Scholar, focusing on studies reporting microbial inactivation performance, operational parameters, and synergistic applications. Results show that UV-LEDs at 265 nm can achieve up to 99% inactivation of *E. coli*, while ozone concentrations around 0.16 ppm demonstrate strong oxidative effects on microbial cells. Combined applications exhibit synergistic effects, enhancing disinfection beyond individual methods. The findings recommend UV-LED and ozone integration as scalable and environmentally safe technologies, particularly suitable for decentralized water treatment in low-resource settings. Future research should emphasize field validation, operational optimization, and integration with complementary technologies. Because of their complementary mechanisms, ozone and UV have synergistic effects when applied together that improve disinfection efficiency. The use of ozone and UV-LEDs as scalable, effective, and sustainable water sterilisation methods is generally supported by this review. These techniques provide a practical route to fulfilling international standards for safe drinking water and are especially well-suited for portable or decentralised water treatment systems.

Keywords: UV-LED · Ozone · Water Sterilization · Microba Contamination · E. Coli · SDGs

INTRODUCTION

Growing urbanisation and population growth continue to put strain on water infrastructure in both urban and rural areas, making access to clean and safe drinking water a vital necessity. (Puji Natalia Kristiani Sitorus et al., 2024; Wolf et al., 2014). Ensuring reliable access to potable water is not only essential for public health but also for social and economic stability (Campos et al., 2022). However, microbial contamination particularly from fecal sources remains one of the most significant barriers to achieving this goal (Novianti & Sulistyorini, 2022). Among various microbial indicators, *Escherichia coli* (*E. coli*) is frequently used as a benchmark for assessing the degree of fecal contamination in water systems, given its prevalence and strong correlation with pathogenic threats (Yin et al., 2018).

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Indonesia, challenges in water safety are intensified by socio-economic inequality and complex geographic conditions that result in unequal access to clean water (Wardhani et al., 2024; Wijayanti et al., 2020). Remote and underdeveloped areas, such as parts of Gunung Kidul Regency in Yogyakarta, continue to rely heavily on limited groundwater resources that often do not meet national drinking water quality standards (Wardhani et al., 2024; Wijayanti et al., 2020). The high cost and limited reach of centralized water treatment infrastructure further exacerbate the risk of microbiological contamination in these regions (Espinosa-Barrera et al., 2024). To address this, various disinfection technologies have been implemented, including reverse osmosis (RO) and ultraviolet (UV) radiation (Yin et al., 2018). While effective in many contexts, these technologies often suffer from limitations related to operational costs, energy consumption, and the inability to maintain microbial safety during long-term water storage (Qonitatul Hidayah et al., 2024; Wijayanti et al., 2020).

Access to safe drinking water is a global challenge, especially in low- and middle-income countries. Traditional methods such as boiling and chlorination are widely used but often insufficient for long-term microbial safety. Recent advances have introduced UV-LEDs, which provide wavelength-specific disinfection at 265 nm without the drawbacks of mercury-based lamps. Similarly, ozone has been used in bottled water industries as a strong oxidizing agent, effective at low concentrations. Current literature highlights growing interest in combining UV-LED and ozone for synergistic disinfection, yet comprehensive reviews remain limited. This paper addresses that gap by synthesizing evidence on their individual and combined effectiveness, identifying operational challenges, and exploring potential for application in decentralized water treatment.

Moreover, the effectiveness of sterilization systems is not determined by technology alone, but also by operational and managerial factors (Andriyanto et al., 2025; Sutiari et al., 2024). Furthermore, while laboratory results may show that refillable water depots meet microbiological safety standards, field studies show inconsistent application of sanitation procedures, documentation practices, and technical oversight; key issues include operator ignorance, inadequate training, and lack of regular maintenance routines. These deficiencies undermine public confidence in such systems and contribute to ongoing exposure to microbiological hazards. Additionally, operating and managerial

Researchers are now looking at more sustainable and sophisticated ways to disinfect water, and two promising methods are ozone (O₃) and ultraviolet light-emitting diode (UV-LED) technologies. UV-LED systems emit ultraviolet radiation at specific wavelengths, especially 265 nm, which is ideal for destroying microbial DNA and stopping cell replication (Yin et al., 2018). Compared to conventional mercury-based UV lamps, these systems have several benefits, such as increased energy efficiency, a longer lifespan, and environmental safety because they don't contain any hazardous materials (Sagai & Bocci, 2011). Conversely, ozone functions as a potent oxidising agent that breaks down microbial membranes and renders pathogens inactive, even at low concentrations like 0.16 ppm, without leaving behind hazardous chemical residues.

In situations where water must be stored for extended periods of time or where there is a persistent risk of contamination during distribution, these technologies are particularly pertinent. But even though they perform well on their own, when combined, they can be even more effective. According to recent research, the combined use of UV-LED and ozone may

offer two inactivation mechanisms: chemical oxidation by ozone and DNA disruption by UV, which together produce a more effective sterilising effect than either technique alone (Ghosh et al., 2024; Song et al., 2016). This dual approach may also be integrated with complementary technologies such as high-voltage electric fields (HVEF) or liquid thin film (LTF) systems to further enhance contact efficiency and microbial inactivation rates.

While the scientific basis for these methods is compelling, various contextual factors must be considered to ensure real-world effectiveness. The performance of UV and ozone disinfection systems depends heavily on raw water quality, including turbidity, pH, and temperature. These parameters can significantly influence light penetration and ozone solubility, thus affecting microbial inactivation. Additionally, the risk of recontamination during post-treatment storage and handling remains a critical challenge. Without appropriate packaging, environmental control, and ongoing monitoring, previously sterilized water may again become a vector for disease transmission.

This review aims to critically evaluate the effectiveness of UV-LED and ozone technologies for sterilizing drinking water contaminated with *E. coli*, both individually and in combination. It also compares their performance to conventional approaches such as boiling and basic filtration, which, while low-cost and accessible, often lack consistency in microbial safety. Furthermore, this review investigates the potential of integrating UV-LED and ozone technologies with emerging methods to enhance efficacy and sustainability in low-resource settings. The goal is to provide a scientific foundation for selecting appropriate water disinfection strategies that are adaptable, energy-efficient, and environmentally sound especially in areas lacking access to centralized treatment infrastructure (Iqbal & Ane, 2022).

PROBLEM STATEMENT AND OBJECTIVE

Access to microbiologically safe drinking water remains a persistent challenge, particularly in regions with limited infrastructure and inconsistent water treatment practices (Diansyukma, 2021). In Indonesia, rural and peri-urban communities often get their water from groundwater or refilled water from local depots. This water may not always meet microbiological safety standards. Many reports and field observations show that even though there are disinfection technologies like reverse osmosis (RO) and ultraviolet (UV) radiation available, waterborne pathogens like *Escherichia coli* (*E. coli*) are often found in stored or distributed water (Iqbal & Ane, 2022). *E. coli*, a primary indicator of fecal contamination, poses significant health risks and serves as a benchmark for evaluating the efficacy of disinfection methods (Novianti & Sulistyorini, 2022).

Conventional sterilization techniques such as boiling and basic filtration, while accessible and widely used, are often inadequate for achieving consistent long-term microbial control. On the other hand, advanced technologies like UV-LED and ozonation, although showing high laboratory efficacy, still face practical challenges related to operational parameters, energy efficiency, and performance during storage and post-treatment handling (Yin et al., 2018). There is also a notable absence of comprehensive evaluations that benchmark these advanced methods against traditional techniques, particularly under real-world conditions reflective of low-resource settings. The problem is further compounded by a lack of awareness and technical capacity among water depot operators regarding sanitation protocols, maintenance schedules, and documentation. This gap in human resource competency, coupled with poor regulatory

enforcement, undermines the effectiveness of even the most advanced treatment systems. Additionally, the long-term microbiological stability of treated water, especially during storage and distribution phases, remains inadequately explored in the context of UV-LED and ozone-based disinfection systems.

The primary objective of this study is to systematically assess the disinfection performance of ultraviolet light-emitting diode (UV-LED) and ozone-based technologies in reducing *Escherichia coli* contamination in drinking water, a key indicator of fecal pollution and microbiological safety. This research aims to compare the effectiveness of these advanced methods against conventional treatments such as boiling and basic filtration in terms of microbial inactivation, operational practicality, and environmental impact. Furthermore, the study seeks to identify critical operational parameters such as exposure duration, ozone concentration, turbidity, pH, and storage conditions that influence the efficacy and sustainability of the disinfection process (Espinosa-Barrera et al., 2024). In addition, it investigates the potential for synergistic effects when UV-LED and ozone are applied simultaneously or in hybrid systems, such as those incorporating liquid thin films (LTF) or high-voltage electric fields (HVEF), to enhance microbial control. Through this review, the study aims to inform the development of more efficient, safe, and accessible water sterilization technologies suitable for resource-limited and decentralized water supply contexts.

RESULT AND DISCUSSION

Ultraviolet light-emitting diode (UV-LED) technology has come a long way in a short amount of time, making it a good replacement for the low-pressure mercury UV lamps that are commonly used in water disinfection systems. UV-LEDs have many benefits, including being more energy-efficient, lasting longer, not containing mercury, being safe for the environment, and being able to be designed in a variety of ways. But more research is needed to find out how well they work as disinfectants, especially since they emit light in a way that is different from traditional UV sources, such as how the intensity is spread out, how specific the wavelength is, and how stable the output is.

The use of ozone and UV to lower *E. coli* levels in drinking water is a very good idea for situations where water is stored before it is used. Studies have shown that ozone levels of about 0.16 ppm significantly lower the number of microbial colonies without going over national ozone exposure limits. This supports the method's safety and effectiveness in both home and industrial settings (Espinosa-Barrera et al., 2024). Ultraviolet-based sterilisation has come a long way, especially with UV-LEDs that work at a wavelength of 265 nm. This method has been very successful at killing bacteria like *Escherichia coli* and *Enterococcus faecalis*. UV-LED and ozone technologies use less energy and are better for the environment than regular mercury lamps. But things like UV wavelength and exposure dosage can affect how well microbial inactivation works (Xue et al., 2023a).

Reverse osmosis (RO) and UV technologies have been extensively studied individually and in combination for their sterilization capabilities (Iqbal & Ane, 2022). This combination has worked well in small-scale settings to lower the levels of coliform and manganese in well water. RO systems are better at lowering turbidity and raising total dissolved solids (TDS) than regular boiling, but there isn't always enough microbiological validation. Other studies have also shown that five minutes of UV exposure can kill coliform bacteria to levels that can't be

detected (0 CFU/100 mL), showing that UV technology could be a good way to make sure water is safe to drink.

Additionally, ozonation at 0.16 ppm has shown high effectiveness in reducing microbial loads in bottled drinking water (AMDK) systems without surpassing safe ozone exposure limits. The synergistic integration of UV and ozone, as well as hybrid methods like liquid thin films (LTF), has demonstrated microbial log reductions up to 5.8 within 30 minutes a performance superior to each individual method (Ling et al., 2022). UV-LED at 265 nm has been validated for its inactivation capabilities against both *E. coli* and *E. faecalis*. The combination of UV with high-voltage electric fields (HVEF) accelerates bacterial cell membrane disruption through complementary physical and chemical mechanisms, further enhancing sterilization efficacy (Iqbal & Ane, 2022; Ling et al., 2022).

A comprehensive overview of recent studies evaluating UV-LED and ozone technologies for the disinfection of *Escherichia coli* in drinking water is presented in Table 1, highlighting key methods, research focuses, strengths, and limitations across various experimental and field-based settings.

Table 1. Summary of Key Studies on UV-LED and Ozone in Drinking Water Disinfection from *E. coli*

No.	Authors	Method	Focus	Strengths	Limitations
1	Hidayah et al. (2024)	RO + UV	Borehole water to bottled water	Improved quality, community education	No economic feasibility analysis
2	Novianti & Sulistyorini (4)	Chlorination	PDAM processing and effectiveness	Simple, effective if source quality is good	Limited microbiological detail
3	Renaldo et al. (2021) (19)	Ozonation (0.10–0.16 ppm)	Ozone effect on AMDK microbiology	Long study, SNI-compliant	No physical parameter consideration
4	Aldelina et al. (2023)	Hygiene observation	Link between depot sanitation and <i>E. coli</i>	Complete microbiological method	No statistical linkage due to absence of <i>E. coli</i>
5	Kamel et al. (2023)	UV-LED (265 & 275 nm)	Reciprocity validation on <i>E. coli</i> disinfection	Systematic UV-LED experiments	Lab-scale, limited organisms
6	Sitorus et al. (2024) (1)	Literature review	<i>E. coli</i> in water sources	Broad review on water types and sanitation policies	No primary data
7	Fajriah et al. (2024)	MPN + observation	AMDK and refill water microbiology	Integrated lab and field observations	Limited to 3 depots
8	Wijayanti et al. (2020) (8)	RO vs Boiling	PDAM treatment effectiveness	Comprehensive evaluation	No direct microbiological testing
9	Fauziah et al. (2021)	UV-C (2, 3, 5 mins)	Contact time effectiveness	Detailed statistical analysis	Only tested coliform
10	Zhang et al. (2024)	UV + HVEF	UV-electric synergy on <i>E. coli</i>	Visual and molecular evidence	Lab-scale, only <i>E. coli</i> tested
11	Lestari et al. (2023) (20,21)	EMBA pH variation	pH effect on <i>E. coli</i> generation	Strong stats, colony visualization	Unrealistic environmental conditions
12	Epelle et al. 2022 (22)	Literature review (UV + O3)	UV-ozone for sterile water	Deep combined-method review	No field testing

No.	Authors	Method	Focus	Strengths	Limitations
13	Fitriani et al. (2023)	Ozone 0.16 ppm	Ozone efficacy in AMDK	Near-zero microbes without SNI exceedance	No method comparison
14	Mufida & Septiawan (2023)	UV + HVEF	UV-electric field combo for E. coli	Fast inactivation via tech integration	Only lab-scale
15	Suryaningsih et al.	UV & O ₃ (3–9 min each)	UV-ozone pasteurization on E. coli, Bacillus	5-log reduction, preserved organoleptic quality	Lower efficacy on Bacillus, no thermal comparison

Recent research trends emphasize the growing interest in multi-modal disinfection systems that combine UV-LED, ozone, and electric field technologies. These integrated methods offer more stable and consistent performance over extended durations. Controlled experiments have shown that a 10-minute ozone contact time can reduce *E. coli* populations by over 90%, though long-term storage post-treatment reveals declining disinfection effectiveness, emphasizing the need for periodic water quality monitoring (Heidt & Landi, 1964; Xue et al., 2023b). Environmental factors such as turbidity, pH, temperature, and storage conditions substantially affect long-term microbiological water safety. The reviewed literature highlights a growing consensus on the efficacy of UV-LED and ozone technologies in microbial water disinfection. Their integration with emerging physical technologies further enhances their potential as sustainable solutions for safe drinking water, especially in low-resource and decentralized settings.

METHOD

This study adopts a narrative review method. Relevant articles from 2018–2024 were identified using keywords “UV-LED water disinfection,” “ozone sterilization,” and “*E. coli* inactivation” across Scopus, PubMed, and Google Scholar. Inclusion criteria were: (1) studies reporting microbial inactivation performance, (2) articles focusing on UV-LED or ozone in water treatment, and (3) English or Indonesian peer-reviewed publications. Excluded were studies unrelated to water sterilization or lacking quantitative results. Approximately 25 primary research articles and 5 review papers were analyzed and compared.

RESULT AND DISCUSSION

Ensuring the microbiological safety of drinking water is critical in preventing waterborne diseases, particularly in regions where centralized treatment systems are either unreliable or absent. Traditional approaches such as boiling and basic filtration, while commonly practiced, are insufficient in eliminating pathogenic microorganisms consistently and sustainably. Moreover, such methods often lack scalability, are time and energy-intensive, and do not guarantee residual microbial safety during prolonged storage (Sutiari et al., 2024). As a key fecal indicator, *E. coli* presence signals the risk of waterborne diseases, including diarrhea, cholera, and gastrointestinal infections. While technologies such as reverse osmosis (RO) and ultraviolet (UV) irradiation are widely adopted for physical and microbiological purification, their efficiency is contingent upon various operational and environmental parameters. Evaluating the energy consumption, sterilization longevity, and adaptability to local raw water characteristics is essential for sustainable application.

Recent studies underscore the promising potential of UV-LED and ozone-based disinfection methods. UV-LED systems, particularly those operating at a wavelength of 265 nm, target microbial DNA with high precision, while ozone serves as a powerful oxidant that disrupts cell membranes and enzymatic pathways. Their combined application especially when augmented with support systems such as liquid thin films (LTF) and high-voltage electric fields (HVEF) has been shown to significantly enhance microbial inactivation rates within shorter treatment durations. However, the success of these technologies depends on raw water parameters such as turbidity, pH, temperature, and organic matter content, all of which influence UV penetration and ozone solubility (Sutiari et al., 2024). Additionally, maintaining microbiological safety post-treatment during storage and distribution remains a critical concern due to recontamination risks.

To ensure effective and sustainable water disinfection, future implementations must be context-sensitive. Disinfection strategies should consider environmental conditions, operational efficiency, and long-term microbial stability. Integrated systems combining UV-LED, ozone, and complementary technologies represent a viable pathway to robust water treatment solutions in decentralized and low-resource environments. However, their field-scale validation remains limited, necessitating further longitudinal and real-world studies.

It is recommended that water sterilization systems be designed not only with advanced technology but also supported by structured sanitation management practices. These include proper documentation, operator training, and public education on microbiological water safety. Hybrid methods such as UV-LED and ozone should be prioritized for broader implementation, offering flexibility across variable water quality scenarios. Finally, consistent community engagement, routine monitoring, and policy support are critical to realizing the full benefits of these disinfection technologies for public health protection.

To address these limitations, this study emphasizes the adoption of ultraviolet light-emitting diode (UV-LED) and ozone (O₃) disinfection technologies as alternative solutions. Both methods have demonstrated high potential in achieving effective microbial inactivation, particularly against *Escherichia coli*, a widely accepted fecal contamination indicator. UV-LED systems operate by emitting ultraviolet radiation at a narrow wavelength optimally around 265 nm corresponding to the peak DNA absorption spectrum. This induces the formation of thymine dimers in microbial DNA, inhibiting replication and leading to cell death. Unlike conventional mercury-based UV lamps, UV-LEDs offer advantages in energy efficiency, compactness, operational safety (mercury-free), and environmental sustainability (Ghosh et al., 2024; Sutiari et al., 2024).

Ozone, a powerful oxidizing agent, offers an additional or complementary mode of action. Upon dissolution in water, ozone generates reactive oxygen species (ROS), including hydroxyl radicals, which target and disrupt bacterial cell membranes, proteins, and nucleic acids. Ozone's capacity to inactivate microorganisms at low concentrations (e.g., 0.16 ppm) without leaving harmful residues renders it highly suitable for both household and industrial water treatment systems (Sutiari et al., 2024). Moreover, its gaseous nature allows even distribution within water systems, improving disinfection uniformity (Ling et al., 2022; Othata & Pochai, n.d.; Wolf et al., 2014).

While each technology individually presents robust disinfection capabilities, recent research supports the strategic integration of UV-LED and ozone for synergistic benefits (Cenci

et al., 2022; Renaldo et al., 2023; Sagai & Bocci, 2011). The simultaneous application can leverage the DNA-damaging effects of UV and the oxidative stress induced by ozone, achieving higher microbial inactivation rates than either method alone (Song et al., 2016). In experimental settings, such combinations have shown bacterial log reductions exceeding 5–6 within short exposure periods, indicating enhanced sterilization kinetics. Furthermore, coupling UV-LED or ozone with high-voltage electric fields (HVEF) or liquid thin film (LTF) systems has demonstrated potential in maximizing contact efficiency and disinfection penetration, especially under challenging water conditions such as high turbidity or variable pH (Cenci et al., 2022).

From a practical perspective, UV-LED and ozone systems are highly modular and can be scaled according to household, community, or industrial needs (Cenci et al., 2022; Sutiari et al., 2024). Their operational flexibility makes them viable for decentralized water supply models, particularly in rural or disaster-prone areas where grid-dependent or infrastructure-heavy systems are infeasible. Importantly, both technologies support automation and can be integrated with sensor-based monitoring to ensure disinfection thresholds are consistently met.

Nevertheless, challenges remain in real-world applications. These include the degradation of ozone during extended storage, reduced UV penetration in highly turbid water, and the potential recontamination of treated water due to poor handling or substandard storage vessels. To overcome these, complementary measures such as post-treatment residuals (e.g., silver-based coatings), proper sanitation training for water handlers, and improved container hygiene must be implemented (Campos et al., 2022; Qonitatul Hidayah et al., 2024; Sarkar & Bharat, 2021). Moreover, regular monitoring and public education on safe water consumption are essential to sustaining the benefits of advanced disinfection technologies.

In summary, the adoption of UV-LED and ozone-based water sterilization represents a scientifically grounded and practically feasible solution to the ongoing challenge of *E. coli* contamination in drinking water. When optimized and integrated appropriately, these technologies can significantly enhance water quality and safeguard public health, particularly in underserved and infrastructure-limited regions.

CONCLUSION

UV-LED and ozone technologies present effective, environmentally friendly solutions for disinfecting drinking water, particularly in inactivating *E. coli*. UV-LED at 265 nm and ozone at safe concentrations offer strong individual performance, while their combination especially when integrated with supporting technologies like LTF and HVEF enhances microbial inactivation efficiency. However, effectiveness depends on water characteristics such as turbidity, pH, and storage conditions. To ensure lasting safety, technical solutions must be supported by proper management, regular monitoring, and community awareness. These technologies are promising for decentralized applications and warrant further field validation for broader implementation.

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