Ultraviolet Disinfection and Chlorination for Wastewater Reuse: A Comparative Analysis and Case Study

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Abstract

Water scarcity is a severe and growing problem in India and worldwide, creating the need to treat wastewater as a resource and expand its safe reuse. Disinfection is an essential stage of wastewater treatment to inactivate pathogenic microorganisms, with chlorination being the long-established method. This study compares ultraviolet (UV) disinfection and chlorination for wastewater reuse across health and safety, sustainability, and life-cycle cost. UV was found to offer substantial advantages for wastewater reuse, principally by eliminating the need for hazardous chlorine chemicals and avoiding the formation of disinfection by-products. Its carbon footprint is expected to become increasingly favourable as electricity grids decarbonise, since its primary energy requirement is electricity rather than chemical production and transport. UV also offers lower and more stable life-cycle costs, despite its higher electricity consumption and equipment costs. Although UV does not provide the residual protection offered by chlorination, this is not a significant disadvantage for non-potable wastewater reuse. A case study of the sewage treatment plant at Trident Nariman Point, Mumbai, where UV disinfection has been used since 2010, demonstrates the practical implementation of the technology in a wastewater-reuse system. The plant treats up to 800 KLD and reuses approximately 65% of its treated wastewater for non-potable applications. Overall, UV disinfection represents a practical and sustainable alternative to chlorination for wastewater reuse.

1. Introduction

1.1 Need for Wastewater Treatment

Water scarcity is a growing problem in India and worldwide. As of 2026, roughly 4 billion people experience severe water scarcity for at least one month each year,[1] while in India nearly 800 million people faced high to extreme water stress as of 2016.[2] This pressure will only intensify over time, as water demand is projected to rise significantly in the coming decades.[3] Hence sustainable solutions to water scarcity are becoming increasingly urgent.

A circular water economy is a sustainability goal that builds climate resilience by increasing the reuse of water.[4] Wastewater is increasingly recognised as a widely available and valuable resource, as affirmed by the United Nations in 2017.[3] However, it cannot be reused directly due to the presence of pathogenic microorganisms, suspended solids, chemical waste, and other contaminants. Hence, leaving wastewater untreated not only has serious health and environmental impacts but also represents a significant lost opportunity. As of 2015, only 30% of India's wastewater is treated,[2] marking wastewater treatment as a field where progress is both essential and full of potential.

Once treated, wastewater can either be discharged into receiving water bodies or reused for non-potable applications such as agricultural irrigation, industrial cooling, landscaping, and toilet flushing.

1.2 Wastewater Treatment Process

Municipal wastewater treatment occurs in three principal stages.[5] These stages are preceded by preliminary treatment, which uses screens and grit chambers to remove large debris, rags, and sand that would otherwise damage or obstruct equipment. Then, the first stage is primary treatment, in which wastewater is held in sedimentation tanks; heavier organic solids sink under gravity to form sludge while lighter fats, oil, and grease (FOG) are skimmed from the surface. Secondary treatment is biological; air is supplied to maintain high dissolved oxygen as microorganisms break down dissolved or suspended organic matter to form activated sludge, which is separated in secondary sedimentation tanks. Finally, tertiary treatment removes fine suspended solids and nutrients through advanced membrane filtration and nutrient-removal processes.

At this stage, treated wastewater can retain bacteria, viruses, and protozoa. Thus, disinfection is essential to inactivate pathogenic microorganisms prior to discharge and reuse. Disinfection effectiveness is quantified using log reduction, calculated as $log_{10}\left(N_0/N\right)$ where N_0 is the initial pathogen concentration and N is the concentration after treatment.[6] Among the available disinfection technologies, chlorination and UV radiation are two of the most widely applied worldwide. These two technologies are the focus of this paper.

2. Chlorination

Chlorination has been the dominant method of wastewater disinfection for over a century, favoured for its low cost, operational simplicity, efficacy against most pathogens, and residual protection downstream from the plant. It remains the most widely used method in India, applied in over 80% of disinfection as of 2023.[7]

2.1 Process

Chlorine is introduced into the treated wastewater in two principal forms. In most large plants it is applied as chlorine gas due to the gas's low cost, whereas small municipal plants often use the more expensive liquid hypochlorite as it is safer to transport than the toxic gas. In gas systems, chlorine is stored in pressurised containers and dissolved into a concentrated solution before being injected into the wastewater stream. The flow then passes along a chlorine contact chamber, which provides the contact time required for the chlorine to act on microorganisms.[8]

Residual chlorine may render the disinfected wastewater unfit for discharge into water bodies as it is toxic to aquatic animals. In such cases, the water is dechlorinated by dosing a reducing agent, such as sulphur dioxide or sodium bisulphite, to neutralise the residual chlorine in the

free and combined form.[8] By contrast, if the disinfected water is destined for reuse, a low residual concentration of at least 0.2 mg/L is maintained to prevent microbial regrowth during pipeline transmission.[9] This chlorine continues to inactivate pathogenic microorganisms, providing residual disinfection.

2.2 Effect

Chlorine dissolves in water to form hypochlorous acid (HOCl) and hypochlorite (OCL^-) ions:[10]

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

$$HOCl \rightleftharpoons H^+ + OCL^-$$

Chlorine destroys target microorganisms by oxidising their cellular material and is effective against a wide range of pathogens.[8] HOCl, which predominates at low pH, is a more rapid and effective disinfectant than OCl^-, which forms mainly at higher pH.[10] Lower pH values allow shorter contact time during chlorination, but reducing the pH risks corroding infrastructure, and regulations restrict the discharge and reuse of acidic treated wastewater. Hence, the pH of the wastewater stream is an important factor to be monitored.

The chlorine dose is the total mass of chlorine added per unit volume of water during disinfection, measured in mg/L. On addition to wastewater, some chlorine is first consumed through reaction with organic matter, ammonia, and other reducing agents.[10] The dissolved ammonia generally present in wastewater reacts with chlorine to form chloramines.[8] As the applied dose increases, the measured chlorine residual first rises as chloramines accumulate, then falls as they are oxidised and destroyed by additional chlorine; beyond a certain dose, known as the breakpoint, additional chlorine persists as free available chlorine. Since free available chlorine is a more effective disinfectant than chloramines, many wastewater treatment plants operate at the breakpoint.[10] However, the dose must be minimised to reduce resource usage and operational cost. Hence, ammonia content of the wastewater should be reduced before chlorination so that fewer chloramines form and the breakpoint is reached at a lower chlorine dose.

3. Ultraviolet Disinfection

Ultraviolet (UV) disinfection has become the principal alternative to chlorination. It is adopted increasingly worldwide and in India.

3.1 Process

UV radiation is generated by mercury arc lamps, which may be low- or medium-pressure. Medium-pressure lamps achieve faster disinfection owing to their higher intensity, but run at higher temperatures and consume more energy; therefore, they are used predominantly in large disinfection facilities. The wastewater passes through reactors perpendicular or parallel to the UV lamps, remaining in the radiation field for a brief contact period. In contact reactors, UV lamps are enclosed in quartz sleeves and immersed directly in the wastewater stream, whereas in non-contact reactors they are suspended outside a transparent conduit

carrying the stream. A ballast (control box) supplies the initial high voltage required to strike the lamps and maintains a stable, continuous operating current.[11]

3.2 Effect

UV radiation penetrates the cell walls of pathogenic microorganisms and damages their genetic material (DNA and RNA), inactivating them by inhibiting their ability to reproduce. The optimum wavelength for this purpose, known as the germicidal wavelength, lies in the range 250 to 270 nm;[11] the industry standard is 254 nm, which mercury lamps can produce very efficiently.[6]

UV dose is the quantity of light energy delivered to microorganisms, defined as the product of UV intensity and exposure time in J/m^2. As per industry standards, a minimum UV dose of 300 J/m^2 is necessary for disinfection. The effectiveness of UV disinfection is influenced by turbidity, total suspended solids (TSS), and UV-absorbing dissolved compounds present in the wastewater, all of which reduce the amount of UV light reaching the microorganisms. This is quantified by the UV transmittance (UVT), the proportion of 254 nm radiation that passes through a 10 mm path of water without being absorbed.[6] A higher UVT allows a given dose to be delivered more quickly and at lower cost, while an insufficient UVT may result in dead zones where the radiation cannot reach microorganisms. Hence, upstream treatment is necessary to increase wastewater's UVT before disinfection. This can be achieved through processes such as filtration and the flocculation of dissolved organic matter and metals.

4. Comparison between Chlorination and Ultraviolet Disinfection

4.1 Health and Safety

The primary risks associated with chlorination stem from the toxicity and corrosivity of chlorine. Leakage of gaseous chlorine during transport, handling, and storage can expose both operators and surrounding populations. Hence, dedicated containment, leak-detection, and emergency-response provisions are necessary.[8] The liquid hypochlorite form bypasses most of these hazards but is far costlier to purchase, transport, and store in large volumes. It is also corrosive and can release toxic chlorine gas if inadvertently mixed with acid.[10]

UV disinfection is a physical process, eliminating the need to produce, handle, and store hazardous chemicals. Though direct exposure to 254 nm UV radiation can cause skin and corneal burns, reactors are fitted with interlocks that deactivate the lamps when accessed by operators, and viewing ports are fitted with UV-filtering windows.[6] Threshold limit values (TLVs) establish safe exposure limits for workers; for 254 nm UV light, the limiting dose is 60 J/m^2.[12] UV systems also present a risk of electric shock as they operate with high-voltage power supplies in close proximity to water, but this risk can be minimised through proper grounding and insulation. Furthermore, the breakage of mercury arc lamps poses a small risk of toxic mercury exposure, which can be addressed through engineering and administrative controls.[6]

Overall, compared to chlorination, UV disinfection is substantially safer, and safety protocols can minimise the risks associated with UV disinfection at a lower cost.

4.2 Sustainability

Chlorination has a significant carbon footprint arising from the manufacture, transport, and storage of chemicals. The industrial production of both chlorine gas and hypochlorite relies on the chlor-alkali process, a resource- and energy-intensive electrolytic process. It requires 2,200 to 3,900 kWh per ton of chlorine gas depending on the type of cell, together with substantial quantities of water.[10] Next, the transport of chlorine or hypochlorite depends on diesel-powered road or rail freight, consuming considerable fuel and generating significant combustion emissions. This footprint scales with dose; if the wastewater contains high concentrations of chlorine-demanding material, more chlorine is required for effective disinfection,[8] increasing the environmental impact of the disinfection accordingly.

As a chemical method, chlorination alters the composition of the treated wastewater. It leaves a residual chlorine concentration that is toxic to aquatic life, so effluent destined for discharge must first be dechlorinated. This step consumes additional chemicals and adds to the overall environmental footprint. Chlorination can also increase the concentration of total dissolved solids and chlorides in the treated water,[8] making it not only hazardous to discharge but also less suitable for reuse in agriculture as chlorides are toxic to plants.

Furthermore, chlorine can react with naturally occurring organic matter and inorganic halides to form disinfection byproducts (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs).[8] DBPs constitute the principal hazard associated with chlorinated water: they pose significant risk to human health even in non-potable reuse such as irrigation, with the United States Environmental Protection Agency classifying certain THMs and HAAs as B2 probable carcinogens.[13] If the treated wastewater is discharged, DBPs are also dangerous for aquatic ecosystems.

The carbon footprint of UV disinfection arises primarily from electricity consumption. Though on-site energy use may be higher for UV disinfection than for chlorination, its upstream energy and resource demands are lower as it does not require the manufacture and transport of chemicals. Moreover, UV has a significantly shorter contact time than chlorination, allowing for smaller reactors and a reduced physical footprint.[11] This lowers the requirement for construction materials such as steel and concrete.

While UV disinfection fails to provide residual protection like chlorination does,[8] this is not a significant disadvantage in wastewater treatment. A chlorine or chloride residual is generally undesirable in water reused in agriculture or industry due to its phytotoxic and corrosive nature. If the treated wastewater is discharged, the absence of a residual is advantageous as it eliminates the need for dechlorination. This residual protection is important primarily in the disinfection of drinking water, which lies outside the scope of this paper.

As renewable forms of energy are increasingly adopted, the carbon footprints of both chlorination and UV disinfection associated with electricity consumption are likely to decline. However, grid decarbonisation does not eliminate the broader environmental burden of chlorination, which also results from the consumption of raw materials to manufacture chemicals, the freight emissions from their transport, and the hazardous chemicals that may remain in the treated water. Thus, UV disinfection is expected to be the more sustainable option for disinfection in the long-run.

4.3 Life Cycle Cost

At the capital stage, UV disinfection requires greater initial investment for equipment—including lamps, reactors, and ballasts—than chlorination. However, this is offset by a number of factors: the absence of dechlorination systems reduces its capital requirement, its lower safety hazards result in lower compliance costs, and its short contact time and compact physical footprint reduce expenditure on land and civil construction. Hence, the capital expenditures for chlorination and UV disinfection are comparable.

Operational expenditures for chlorination are high due to the continuous cost of chlorine or hypochlorite and of reducing agents used in dechlorination. It also entails greater labour costs, as hazardous chemicals require certified operators for handling, continuous testing and calibration, and active safety management. By contrast, UV disinfection is simpler to operate and largely automatic, and it requires less frequent maintenance. Its operational expenditure arises principally from its high electricity demand, but the power utility costs are lower than the spending on chemical and specialised labour required for chlorination. Thus, overall, the operational expenditures of UV disinfection are lower than those of chlorination.

Furthermore, chlorination relies on continuous, bulk shipments of disinfectants and neutralising agents. Consequently, its operating cost is vulnerable to external market shocks and volatility in the price of chemical commodities and fuel, whereas UV disinfection poses fewer financial risks.

The costs associated with both disinfection methods have been summarised in Table 1. Overall, due to these factors, it can be concluded that UV disinfection is economically superior to chlorination over a full operational life cycle.

Table 1. Comparison between chlorination and UV disinfection in terms of costs

	Cost Parameter	Chlorination	UV Disinfection
Capital Expenditure	Land and Civil Construction	High	Low
	Primary Disinfection Equipment	Low	High

	Cost Parameter	Chlorination	UV Disinfection
	Dechlorination Systems	Medium	Zero
	Safety and Risk Compliance	High	Low
Operational Expenditure	Chemicals	High	Zero
	Electricity	Low	High
	Labour	High	Low
	Maintenance and Replacement	Low	Medium
Financial Risk	Supply Chain Volatility	High	Low

5. Case Study: Trident Nariman Point, Mumbai

5.1 Introduction

The hospitality sector is a substantial consumer of water and therefore produces significant volumes of wastewater. Demand is especially high in large luxury hotels, which combine restaurants, spas, swimming pools, landscaped grounds, commercial kitchens, laundries, and numerous bathrooms. Because hotel effluent mixes wastewater from kitchens, laundry, and maintenance, it is often unsuited to conventional municipal sewage treatment, creating a need for decentralised, hotel-specific systems.[14]

This case study examines the wastewater treatment plant at Trident Nariman Point, Mumbai, in operation since 1973. The hotel adopted UV disinfection in 2010 to enable wastewater reuse; the system is supplied and maintained by Alfaa UV. The plant has been the subject of previous research, including a study evaluating the performance of its submerged ultrafiltration membrane bioreactor system.[14] This case study focuses on the plant's UV disinfection system.

5.2 Benefits to Society

The plant treats the hotel's entire wastewater output, up to its capacity of 800 kilolitres per day (KLD). It reuses approximately 65% for non-potable purposes, including cooling towers, toilet flushing, gardening, and car washing, with the remainder safely discharged to a local sewer line. By recovering and reusing treated wastewater, the plant supports more sustainable water management, while its decentralised design reduces the load on municipal wastewater infrastructure.

5.3 Treatment Process

The plant operates continuously and comprises two streams: an effluent treatment plant (ETP) handling kitchen and laundry wastes (trade effluent), and a sewage treatment plant (STP) handling greywater and blackwater from bathrooms and toilets (domestic sewage). A flowchart of the plant is shown in Figure 1. In the ETP, the trade effluent passes through a bar screen to remove large debris and then a flocculation-cum-settling tank, where alum coagulation, polyelectrolyte flocculation, and anti-foam dosing are carried out, along with the clarification of the settled solids. The domestic sewage is similarly screened before the two streams combine and pass to the STP for primary, secondary, and tertiary treatment.

In the STP, FOG are removed in an oil and grease trap, after which the effluent is buffered in an equalisation tank to stabilise the flow rate, and a drum screen is used to separate fine suspended solids. The wastewater is then denitrified by bacteria in an anoxic tank and treated biologically in an aeration tank to break down organic matter. A membrane bioreactor provides secondary clarification and ultrafiltration, with regular backwashing clearing trapped particulates from the membrane pores; this stage also raises the UVT of the effluent by substantially reducing TSS.[14] The treated water then undergoes UV disinfection before collection in a treated-water tank. Returned activated sludge, rich in bacteria and nitrates, is recirculated to the anoxic tank to enhance denitrification, while excess sludge is flocculated with polyelectrolyte, dewatered by centrifuge, and sent to an organic waste converter to produce compost.

Operation is automated by a supervisory control and data acquisition (SCADA) system. The SCADA interface is shown in Figures 2 and 3. This enables real-time monitoring of parameters such as turbidity and dissolved oxygen, immediate alerts on leakage or failure, and optimised energy use with minimal manual oversight.

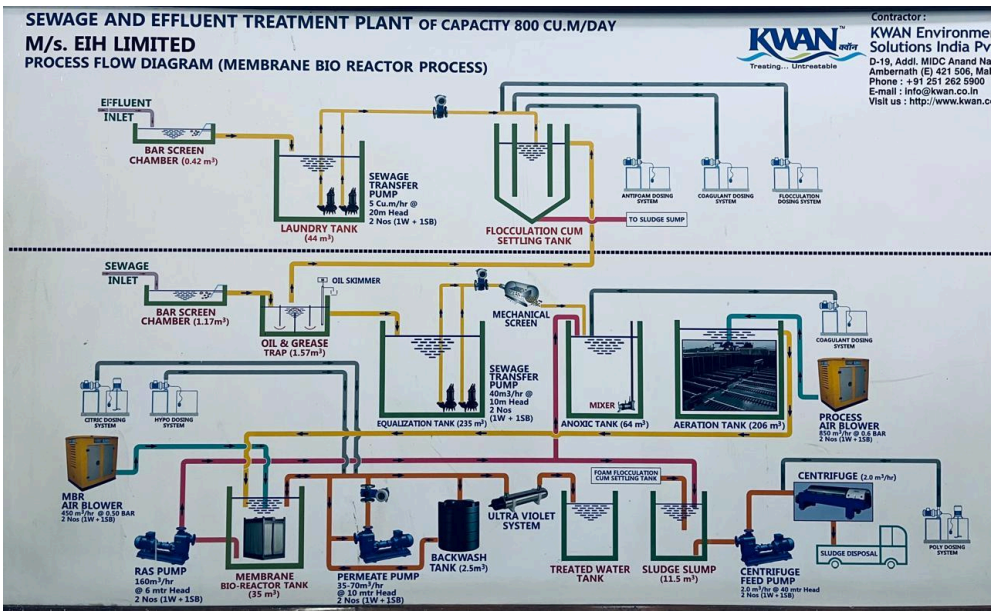


Figure 1. Process flow diagram of the sewage and effluent treatment plant at Trident Nariman Point, Mumbai. Lines indicate process connections and arrows indicate the direction of flow. The photograph was taken during a site visit on 11 August 2026.

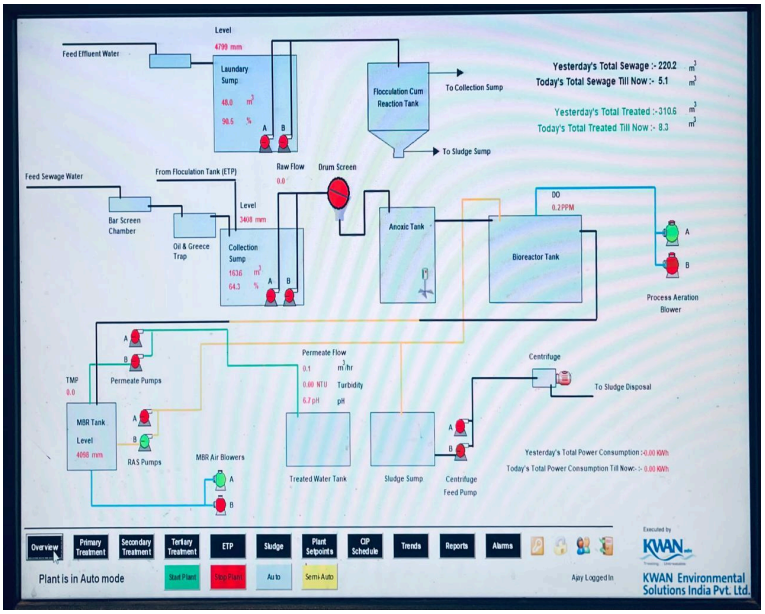


Figure 2. SCADA overview of the sewage and effluent treatment plant at Trident Nariman Point, Mumbai. Lines indicate process connections. The photograph was taken during a site visit on 11 August 2026.

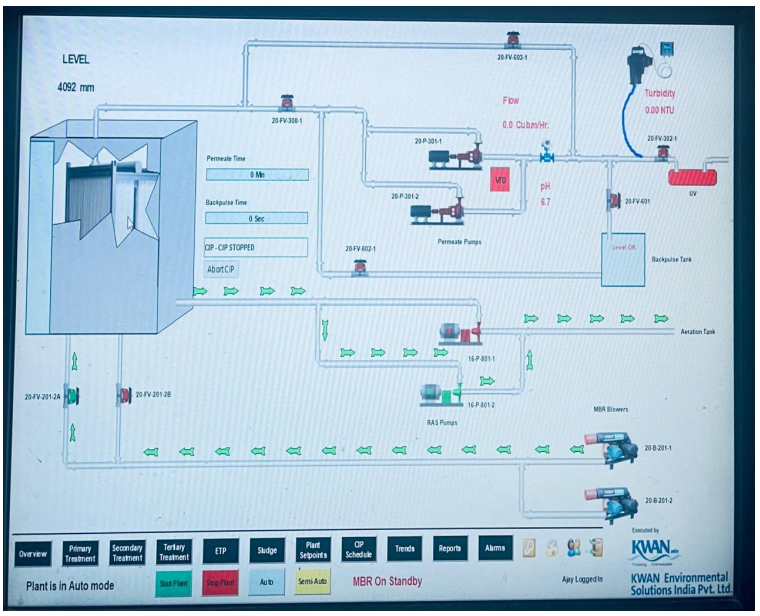


Figure 3. SCADA interface for the tertiary treatment stage at Trident Nariman Point, Mumbai. Lines indicate process connections and arrows indicate the direction of flow. The photograph was taken during a site visit on 11 August 2026.

5.4 UV System

Supplied by Alfaa UV, the UV disinfection system consists of a HF-1 series UV reactor integrated with a UVM5000 real-time intensity monitor. An image of the UV system is shown in Figure 4. It uses low-pressure mercury lamps in a contact reactor. The reactor processes a residence time of 4.42 s and a design flow rate of 18 m^3/hour through an effective chamber volume of 22.12 L. When fitted with new lamps, the system operates at a nominal intensity of at least 50 W/m^2, delivering an initial nominal UV dose of over 944 J/m^2. As lamps age over their 12,000 hour rated lifespan, output declines. The UV meter measures real-time output against a cutoff intensity threshold of 21.19 W/m^2, ensuring that the unit consistently delivers a minimum cutoff dose of 400 J/m^2 to ensure compliance above the standard industry minimum for water disinfection (300 J/m^2). The reactor coefficient for this model is 4.27. The parameters of the UV system, derived using lamps aged 100 hours and using water having UVT 98%, are summarised in Table 2. A high UVT is achieved through the MBR system.

The system is maintained by Alfaa UV on a monthly basis. This involves servicing the quartz sleeves, UV sensors, and contact chamber. During servicing, the quartz O-ring holding the UV lamp may need to be replaced if damaged, and the lamp must be replaced after 12,000 hours of use. Certain safety measures must be followed during servicing: the valves are closed, the chamber is drained, and the power supply is switched off.



Figure 4. UV disinfection system installed at the sewage treatment plant at Trident Nariman Point, Mumbai. It includes a High-Flow HF-1 series UV reactor (centre) and a UVM5000 real-time intensity monitor (right). The photograph was taken during a site visit on 11 August 2026.

Table 2. Parameters of the UV disinfection system at Trident Nariman Point, Mumbai

Characteristic	Value
Model name	HF-1 series UV reactor
UV meter	UVM5000 intensity monitor
UV radiation wavelength	254 nm
Lamp life	12,000 hours
Target UV dose	> 400 J/m^2
Nominal UV dose	> 944 J/m^2
Cutoff UV dose	> 400 J/m^2
Nominal intensity	> 50 W/m^2
Cutoff intensity	> 21.19 W/m^2
Effective chamber volume	22.12 L
Flow rate	18 m^3/hour
Residence time	4.42 s
Reactor coefficient (at 98% UVT)	4.27

5.5 Plant Performance and Regulatory Compliance

The performance of the water treatment plant relative to regulatory limits, last updated on 1 January 2024, is shown in Table 3. The plant meets the permitted limits for all the measured parameters.

Table 3. Plant operating parameters and regulatory limits at Trident Nariman Point.

Category	Parameter	Specified Limit	Actual Value
Hydraulic flow	Trade effluent	309 m^3/day	238 m^3/day
	Domestic sewage	468 m^3/day	358 m^3/day
	Total combined flow	777 m^3/day	596 m^3/day
Treated wastewater quality	pH	6.5–9.0	7.2
	BOD (3 days at 27°C)	10 mg/L	5 mg/L
	COD	50 mg/L	30 mg/L
	Total dissolved solids	Not specified	250 mg/L
	Suspended solids	20 mg/L	8 mg/L
Solid waste	STP sludge	40 kg/day	20 kg/day

6. Conclusion

In conclusion, this study compared chlorination, the long-established method, with UV disinfection across health and safety, sustainability, and life-cycle cost. UV disinfection was found to present several advantages over chlorination: it poses fewer safety hazards, avoids the formation of harmful DBPs, adds no chemical residual to the water, and may be the more economical option over a full operational life cycle. It is also the more sustainable technology and is expected to result in a smaller carbon footprint as energy generation decarbonises. Chlorination retains an advantage in its lasting residual, but this is less significant for reused wastewater than for potable water; it can even be undesirable in certain applications.

The case study of the sewage treatment plant at Trident Nariman Point demonstrates the practical application of UV disinfection in an operating wastewater-reuse system. The plant has a capacity of 800 KLD and reuses approximately 65% of its treated wastewater for applications including cooling, flushing, gardening, and car washing. The long-term operation of the UV system shows that UV disinfection can be successfully incorporated into decentralised wastewater treatment systems.

Overall, the comparison conducted in this study suggests that UV disinfection is generally a more suitable alternative to chlorination for wastewater treatment. As water scarcity becomes an increasingly pressing problem, the effective treatment and reuse of wastewater can reduce demand for freshwater and contribute to a circular water economy. UV disinfection represents a practical step towards sustainable water management.

This study is limited in scope. It addresses only wastewater disinfection and restricts the comparison to chlorination and UV. Future work could extend to drinking-water treatment, where residual protection plays a more significant role, and broaden the comparison to other disinfection technologies such as ozonation. Furthermore, it would be useful to examine a larger set of wastewater treatment plants and draw on long-term operational and cost data to reinforce the conclusions reached here.

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