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# Disinfection Methods

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Additional information is available at the end of the chapter

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## Abstract

Water must be made safe to drink, and an important step in ensuring water safety is disinfection. Disinfectants are added to water to kill disease-causing microorganisms. Ground water sources can be disinfected by “The Water Treatment Rule,” which requires public water systems for disinfection. Chlorination, ozone, ultraviolet light, and chloramines are primary methods for disinfection. However, potassium permanganate, photocatalytic disinfection, nanofiltration, and chlorine dioxide can also be used. Organic material is naturally present in water. Certain forms of chlorine can react with these organic materials and result in the formation of harmful by-products; the U.S. Environmental Protection Agency has anticipated maximum levels for these contaminants.

**Keywords:** chlorination, chloramines, ozone, ultraviolet light, photocatalytic disinfection

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## 1. Introduction

Killing, removal, or deactivation of harmful microorganisms can be referred to as disinfection. Destruction or deactivation of pathogenic microorganisms results in stopping their reproduction and growth. People may fall ill by consuming the contaminated water containing the pathogenic microorganisms. Disinfection and sterilization are interrelated processes, but sterilization kills all the harmful and harmless microorganisms. Hence, disinfection is a more appropriate process.

## 2. Methods of disinfections

### 2.1. Chlorine Gas

Chlorine is a greenish-yellow gas. By providing high pressure, the gas becomes liquid. It is toxic. Chlorine gas is mostly used as a water disinfectant. Introducing chlorine to water plays a very effective role for removing almost all pathogenic microorganisms. It can be used both as a primary and a secondary disinfectant. The gas is not applicable to be used in household system as it is very dangerous. It is lethal at concentrations as low as 0.1% air by volume [1].

#### 2.1.1. Advantages

- Chlorination is a cheaper source than UV or ozone disinfection methods used to treat water.
- It is very effective against a wide range of pathogenic microorganisms.
- Dosing rates are controlled easily as they are flexible.
- The chlorine residuals left in the wastewater effluent can make the disinfection process longer even after initial treatment. They can be further used to evaluate the effectiveness [2].

#### 2.1.2. Limitations

Although chlorine gas is used in large-scale water distribution treatment plants and networks as a best method for treating water, still it have various limitations. These limitations might affect the applicability to a point of use (POU) treatment system. Objections against chlorination are because of the esthetic, logistic, and health-related concerns.

Regarding esthetic level, chlorination might be rejected as it imparts bad tastes and odors to the water. The developed countries might teach their people about the good impacts of chlorination; however, less-developed countries lack this ability.

Limitations in using chlorine gas in a household context might include the distribution, procurement/manufacturing, dosing of chlorine, and accurate handling. The health hazards caused by chlorine are not only confined to its volatile nature. A great concern might be the byproducts and incompletely oxidized compounds present in chlorinated water that increases its toxicity. The most notorious byproducts of chlorination are chloro-organics and trihalomethane (THMs). Humic and fulvic acids are present in the water. When chlorine reacts with these acids, trihalomethane are formed. It has been identified in many studies that some of these chloro-organics are mutagens, toxins, or carcinogens. The well-known THM chloroform is an animal carcinogen. Some guidelines have been set by USEPA (United States Environmental Protection Agency) that THMs should not be greater than 0.10 mg/l. The high concentrations of THMs will lead to health complications [1].

### 2.1.3. Process

Chlorine readily combines with all the water components, i.e., chemicals, small animals, microorganisms, plant material, odors, colors, and tastes. Sufficient quantity of chlorine is necessary to meet with the demand of chlorine in the water and provide residual disinfection.

Residual (free) chlorine is termed as the one that does not combine with other water components. The point at which free chlorine is available for continuous disinfection is termed as the breakpoint. The system at which free chlorine is supplied at a concentration of 0.3–0.5 mg/l is an ideal system. Simple test kits, most commonly the DPD (N,N-diethyl-p-phenylenediamine) colorimetric test kits are available for testing breakpoint and chlorine residual in private systems. The kit must test the amount of free chlorine, not total chlorine [3].

### 2.1.4. Equipment

This consists of 908 kg (2000 lb) or 68 kg (150 lb) containers, weigh scales, chlorinator, injectors, switchover modules, vacuum lines, booster pumps, solution lines, diffusers, and a flow meter. Safety requirements are passive ventilation, mechanical ventilation, warning alarms and devices, showers, panic hardware for doors, and eye washes. A separate air tight room for chlorination equipment is mandatory. For disinfection process, 100% of chlorine gas is available [4].

### 2.1.5. Chemical

Chlorine can be used as liquid or gas form. It is a very strong, oxidizing agent. Both the forms (liquid and gas) can be stored and used from gas cylinders under pressure. The chlorine cylinders can be 150 pounds. Small drinking water systems commonly use cylinders of 150 pounds.

Hypochlorous and hypochlorite ions are formed when chlorine is mixed with water. The hypochlorous ion is a better disinfectant which is formed in greater concentration at low pH concentrations. The hypochlorite and hypochlorous ions will be present in equal concentrations at pH 7.3. At pH above 8.3, the hypochlorite ion predominates which is not a better disinfectant. So, better disinfection is achieved at low pH. To avoid the formation of trihalo-methanes and haloacetic acids, chlorination should be applied after treatment [5] (**Figure 1**).

## 2.2. Chlorination (sodium hypochlorite solution)

Sodium hypochlorite is used as a bleaching agent, mostly to bleach papers or textiles, and as a disinfectant in solution. The solution generally contains 10–15% of the available chlorine, but rapidly loses its force in storing process. Regular controlled environment is needed as the solution is affected greatly by the pH, light, heat, and heavy metals [6].

### 2.2.1. Advantages

- Sodium hypochlorite can also be used as a disinfectant.
- Both sodium hypochlorite and chlorine gas shows similar disinfection effectiveness.

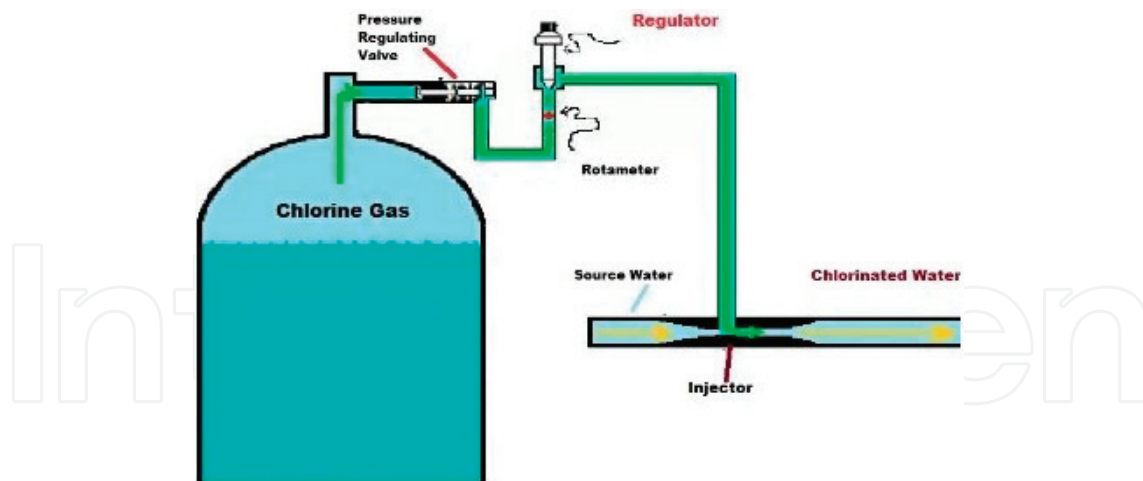


Figure 1. Chlorination by gas method.

- As compared to chlorine gas, sodium hypochlorite disinfection reduces the hazards in storing and handling.
- No hazardous chemicals are used in onsite generation. Only softened water and high grade salt (NaCl) is used.
- As compared to the standard supplied solution (14% concentration), sodium hypochlorite (NaOCl) solutions are less hazardous (1% concentration) and less concentrated while generating onsite production [7]

### 2.2.2. Limitations

NaOCl can be commercially supplied or generated on-site, the latter being the safer of the two methods for handling reasons. In on-site generation, salt is dissolved with softened water to form a concentrated brine solution that is subsequently diluted and passed through an electrolytic cell to form sodium hypochlorite. Hydrogen is also produced during electrolysis, and it needs to be vented because of its explosive nature [7].

### 2.2.3. Process

These dosing systems are mostly simple, but there might be a concern regarding the design. The design might influence the control of gas release from the bulk hypochlorite in dosing pumps and piping and scale formation. Gasification (mostly produces oxygen) can lead to vapor or gas bubbles' formation, specifically if sodium hypochlorite is below the atmospheric pressure, which leads to gas locking of the suction line in a diaphragm. Pumps should therefore be provided with flooded suction. Tanks must be properly vented out of all structures to the atmosphere.

Most commonly available dosing systems use diaphragm metering pumps. The pump action can lead to the development of vacuum. The vacuum causes the vaporization of the dissolved gases in the sodium hypochlorite, resulting in the pump losing its prime and a lower applied chlorine dose.

Consequently, to aid in the prevention of gasification, the dosing arrangements must have a positive head on the pump suction (with pump inlet always below the minimum tank liquid level). In addition, piping system configurations which will trap sodium NaOCl between two closed isolation valves or check valves should be avoided.

A calibration cylinder, a pulsation damper, a pressure relief valve, and a loading valve are the main components of a dosing system. Automatic auto-degas valves systems are also provided by some dosing pump suppliers. NaOCl is dosed either through a spreader bar submerged within an open channel or through an injection fitting (pressurized pipes). The pulsation damper and the dosing pump should be placed close to each other. Pulsation damping also helps in improving dispersion. A loading valve should also be provided in systems where the back pressure at the pump delivery side is not sufficient (<0.7–1.0 Bar), till a suction demand valve is installed on the suction side.

For protecting the diaphragm from rupturing, a PRV (pressure relief valve) should also be provided on the delivery side of the pump. PRV's operation must be detected and alarmed: e.g., the outlet of the valve could be directed to a small "catch-pot," equipped with a float switch. All the systems or pumps which are shut down should contain methods to relieve any pressure buildup.

As sodium hydroxide (NaOH) is used in its manufacturing, the pH of NaOCl is high. Extreme care is needed when using hard waters (or waters with CO<sub>2</sub> present), as the highly alkaline product can lead to lower flow rates, reduced pipe diameter, reduce pump capacities, and scale formation at dosing points [8].

#### 2.2.4. Equipment

NaOCl solution is a corrosive liquid with a high pH, i.e., 12. So, general precautionary measures for dealing with corrosive materials should be used such as avoiding metal contact, including stainless steel. These solutions might contain chlorate. Due to product degradation, chlorate can be formed during the processes of manufacturing and storage of sodium hypochlorite. The formation of chlorate and the degradation of NaOCl are directly related to each other. By reducing the degradation of NaOCl, the formation of chlorate can be minimized by avoiding high temperatures, reducing light exposure, and through limiting storage time. Spill containment should be provided for the NaOCl storage tanks. Typical spill containment structures include no uncontrolled floor drains, containment for the entire contents of the largest tank (along with the freeboard for rainfall/fire sprinklers), and separate containment areas for each incompatible chemical [9].

#### 2.2.5. Chemicals

NaOCl solution (or liquid bleach) is a solution with 5–15% concentration of chlorine. It is used as bleaching and cleaning agent. It is also used extensively as water disinfectant, but it may not be the most economical solution as it is more expensive than gas. Being liquid, it can be handled easily than gas or calcium hypochlorite, but it is limited by its lack of stability and corrosive nature. It can be produced easily. Continuous supply of salt and electricity is needed for onsite generation of liquid bleach. Liquid bleach has a better POU application because of its availability and relative manageability [1] (**Figure 2**).

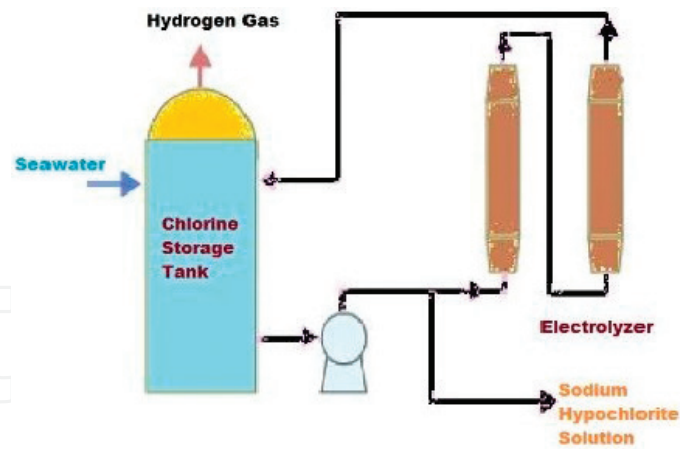


Figure 2. Chlorination by chlorine liquid method.

### 2.3. Chlorination (solid calcium hypochlorite)

$\text{Ca}(\text{OCl})_2$  (calcium hypochlorite) is an essential solid that can be used in replacement of  $\text{NaOCl}$  (liquid). As a disinfectant, it has similarity with  $\text{NaOCl}$  but it is much safer to handle. Almost 70% of chlorine is available in commercial grades of  $\text{Ca}(\text{OCl})_2$ . It has applications in both waste water and drinking water [7].

#### 2.3.1. Advantages

- Being solid,  $\text{Ca}(\text{OCl})_2$  is more safer than chlorine gas and  $\text{NaOCl}$ .
- It even has excellent stability when stored in dry place, maintaining its potency well over time [7].

#### 2.3.2. Limitation

Contamination or improper use of  $\text{Ca}(\text{OCl})_2$  may lead to explosion, fire, or the release of gases (toxic gases). Calcium hypochlorite should not be allowed to contact any foreign matter (including other water treatment products). If  $\text{Ca}(\text{OCl})_2$  is exposed to even very small amounts of water, it can react violently to produce toxic gases, heat, and spatter. Product should be added to water instead of adding water into the product. Exposure to heat can cause  $\text{Ca}(\text{OCl})_2$  to decompose rapidly, which may lead to explosion, intense fire, and the release of toxic gases. Dry, cool, well-ventilated area is needed for storing the product.  $\text{Ca}(\text{OCl})_2$  is used as a strong oxidizing agent. It increases the intensity of fire.  $\text{Ca}(\text{OCl})_2$  must be kept away heat, i.e., flame, heat, and any kind of burning materials [7].

#### 2.3.3. Process

The calcium hypochlorite chlorinator contains a cylindrical polyvinyl chloride (PVC) tank with a height of 0.6–1.2 m and a diameter of 230–610 mm. A sieve plate is present containing holes that support the 80 mm diameter  $\text{Ca}(\text{OCl})_2$  tablets. Tablet chlorinator systems can



usually provide between 1 and 295 kg of chlorine per day. At the bottom, a side stream is piped into the chlorinator. The flow arises from the holes in the sieve plate that results in eroding the last layer of tablets. The amount of water entering the chlorinator is proportional to the rate at which the tablets erode. The rate of chlorine dosage can be calculated by controlling the water flow through the chlorinator. To meet the operational requirement, the chlorinator effluent is returned to the main stream, providing the desired level of available chlorine.

Variation in the dose and the contact time can be done to calculate the required disinfection. Different factors affect the chlorine dosage, i.e., wastewater characteristics, the demand of chlorine and discharge requirements. Mostly, the dose ranges from 5 to 20 mg/L. Different factors account for optimum disinfection that might include temperature, alkalinity, and nitrogen content. The pH of wastewater might affect the distribution of chlorine between hypochlorous acid and hypochlorite. A lower pH favors the hypochlorous acid: a better disinfectant. Higher concentrations of hypochlorous acid will lead to the formation of hazardous chlorine gas [2].

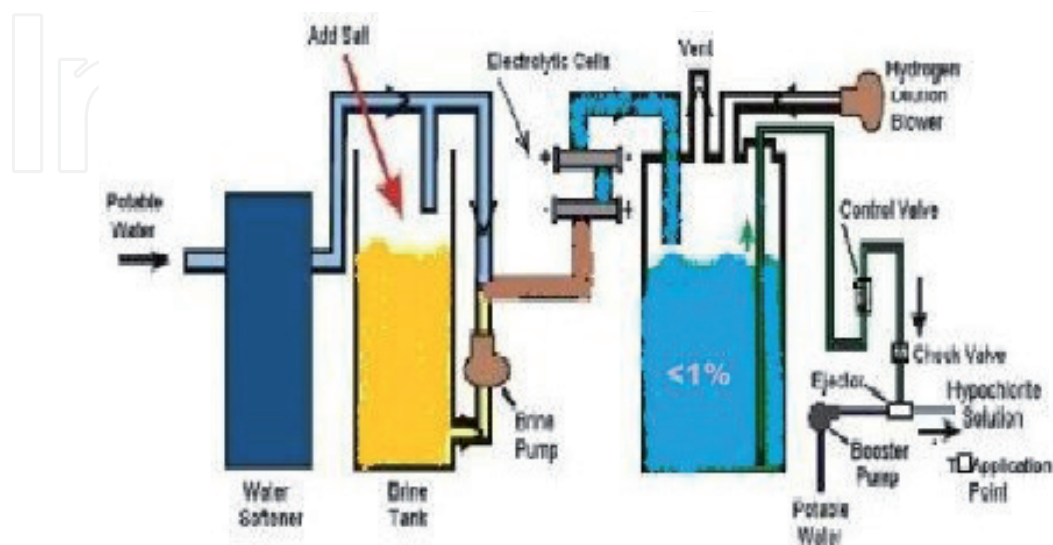
#### 2.3.4. Equipment

$\text{Ca}(\text{OCl})_2$  can be added to the wastewater by two ways, i.e.,

1. Either by mixing calcium hypochlorite powder in a mixing device and then injecting it into the wastewater stream;
2. By immersing chlorine tablets in the wastewater using a tablet chlorinator [2] (**Figure 3**).

#### 2.4. Chloramines

Chloramines are formed by reacting ammonia with free chlorine. They play an important role in providing residual protection in the distribution system. They are very stable. In comparison to chlorine, fewer halogenated by-products are formed [10].



**Figure 3.** Chlorination by calcium hypochloride method.

### 2.4.1. Advantages

- Chloramine is more stable but not a strong disinfectant as chlorine, providing long lasting residual disinfectant.
- No by-products are formed in chloramination.
- However, the environmental protection agency (EPA) is eager to know about the type and quantity of disinfection byproducts produced by the interactions of chloramines, bromide, brominated organics, and by the chloramination of ozonized waters. EPA's findings may influence chloramine's future use [7].

### 2.4.2. Chloramination equipment

Equipment for both the production of chloramines and chlorination systems are same. Both chlorine and ammonia might be introduced as a liquid or gas. Additionally, both chlorine and ammonia are available in liquid or granular form. Great care must be taken so that concentrated chlorine and ammonia are never mixed as they will form nitrogen trichloride, a potentially explosive compound [11].

## 2.5. Ozonation

Ozone is an allotropic (unstable) formula of oxygen in which three molecules are combined to produce a new molecule. It quickly decomposes to generate highly reactive free radicals. The ozone's oxidation potential ( $-2.7$  V) is greater than that of the chlorine ( $-1.36$  V) or hypochlorite ion ( $-1.49$  V), substances widely used in wastewater treatment such as oxidants. Ozone is surpassed only by the hydroxyl radical ( $\bullet\text{OH}$ ) and fluoride in its oxidation capacity [7, 12].

### 2.5.1. Advantages

Following are the advantages when ozone is used to treat water:

- Ozone possesses strong oxidizing power
- Short reaction time is needed so germs (including viruses) are killed in a few seconds
- No change in color and taste occurs.
- Requires no chemicals
- Oxygen is provided to water after disinfection
- Destroys and removes algae
- Oxidizes iron and manganese
- Reacts with and removes all organic matter [13].

### 2.5.2. Limitation

Onsite generation is necessary as ozone is unstable at atmospheric pressure. It is toxic in high concentrations as it is a greenhouse gas. The three modules of an ozone plant are ozone

destructor, ozone contact chamber, and generator. UV light or the corona discharge process is used for ozone generation. In contact chamber, ozone is added to water. The main purpose of the destructor is to limit the amount of ozone to be stripped out into the air. Three main processes affect the release of ozone after introducing ozone into water: decomposition, reaction with water impurities, and stripping into the atmosphere [14].

### 2.5.3. Process

Ozone is produced from a gas containing oxygen (usually ambient air or pure oxygen). The gas is then passed through an electric field. The air is treated to make sure that it is dry and free from dust impurities. Oxygen is converted to ozone in an electrical field. The ozone is then fed to the contact tank so that ozone is dissolved by water to proceed disinfection process [14].

### 2.5.4. Equipment

The system consists of a combination of oxygen supply and high power electric supply systems: a high voltage electric current flow between electrodes and oxygen is discharged between the electrodes. Electrodes are separated with the help of a dielectric gap that contains the discharge chamber for oxygen flow. Electric field causes the breakdown of oxygen molecules and formation of ozone occurs. After generation, the ozone is directed toward the connection chamber, where the treated water is to be disinfected. The ozone produced will dissociate immediately so onsite generation of ozone must be done.

One of the important features is the contact time as well. So, the ballasting and the deballasting modes of very large ballast amounts of water will be much expensive in full-scale applications. One or several ballast water are equipped with ozone injection equipments that act as contact chambers. For achieving long contact time, that ballast water should be pumped into these contact tanks. In order to reduce the sediment formation and fine particles to enter the treatment process, the ozone treatment must undergo preliminary treatment (filter or cyclone).

The ballast treatment ensures that the all the water present in ballast tanks is exposed to ozone at the beginning of the voyage. Contact time plays an important role in the disinfection process. Disinfection is ensured if long contact is not required against the specific microorganism. If long contact time is required against specific microorganisms, treatment should be done during voyage to enable longer contact times.

Organic carbons are associated with sediment formation. These sediments settle down at the bottom of the ballast tanks during voyage. The sediments contain the microbes that are difficult to treat like bacterial colonies or viral clumps. Ozone treatment might not be efficient in the sediment. Ammonia might be produced as a result of biological activity during voyage. Bromines are produced by the reaction of ammonia and disinfectant residual. Bromines are weaker disinfectants, thus the efficacy is reduced [14].

### 2.5.5. Chemical

Ozone is produced by applying high voltage electricity to a gap (tube) containing pure oxygen or filtered dry air (corona discharge method).

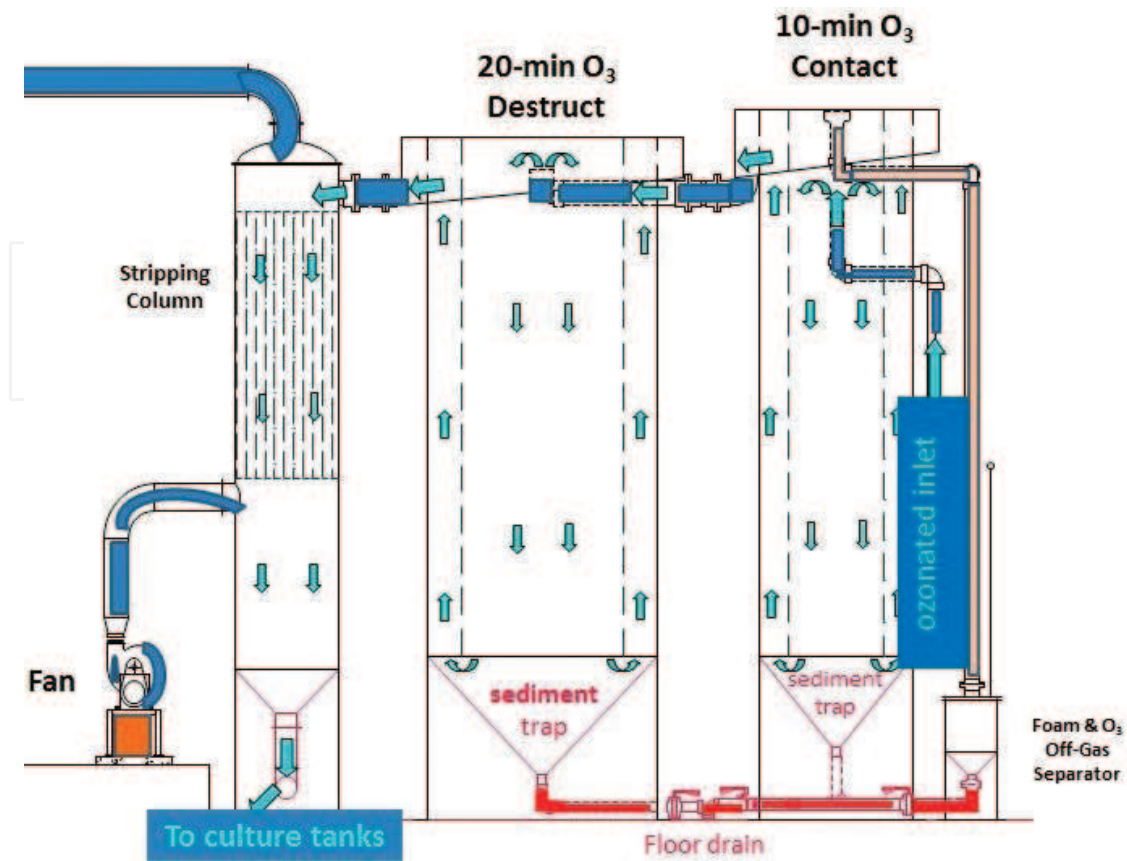
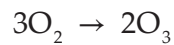


Figure 4. Ozone contacting.

The high voltage electricity results in the formation of ozone by recombining oxygen. The reaction is as follows:



Ozone disinfects by oxidizing the cell walls of microorganisms, which then disintegrates (lyse), destroying the microorganism. This is a very different mechanism than with chlorine, which diffuses through the cell wall, making the cell susceptible to enzymatic attack [7] (Figure 4).

## 2.6. Ultraviolet light (UV)

UV treatment can be used for treating waste water, drinking water, and aquaculture. The UV light causes disinfection by changing the biological components of microorganisms specifically breaking the chemical bonds in DNA, RNA, and proteins [14].

### 2.6.1. Advantages

- It limits the regrowth potential within the distribution system so no increase in the concentration of biodegradable or assimilable organic carbon (AOC) occurs.

- With respect to interactions with pipe material, there are no concerns.
- No by-products are formed (e.g., hemoglobin-associated acetaldehydes (HAA), trihalo-methanes (THM), aldehydes, ketoacidosis, and bromate).
- By using UV light we can achieve the same log inactivation of *Giardia* and *Cryptosporidium*, less in cost either than chlorine dioxide and ozone techniques.
- When used in relation with chloramines, no formation of chlorinated disinfection by-product (DBP) is noticed [14].

### 2.6.2. Limitations

In underdeveloped countries, there are several limitations for UV disinfection. The major limitation is the energy requirement. In many systems, the electric power supply cannot be guaranteed.

A limitation might be that there is not even a single test available to examine the proper disinfection of the rays. It is only effective as a primary disinfectant as it does not leave any residues. It does not act as a secondary disinfectant as it does not work against reinfection in water.

A concern regarding the UV disinfection is chemical composition and the quality of microorganisms present in the influent water. Turbid, cloudy, or the water containing a large number of bacteria can be used to shield bacteria. Chemical composition is a basic problem as the water containing large amount minerals might cause coating on the lamp sleeve, thus reducing the effectiveness of the treatment. Phosphate injectors or water softeners can be used to prevent lamp coating. UV treatment is more effective on low turbid water or partially treated water, which may not be available in the field [15].

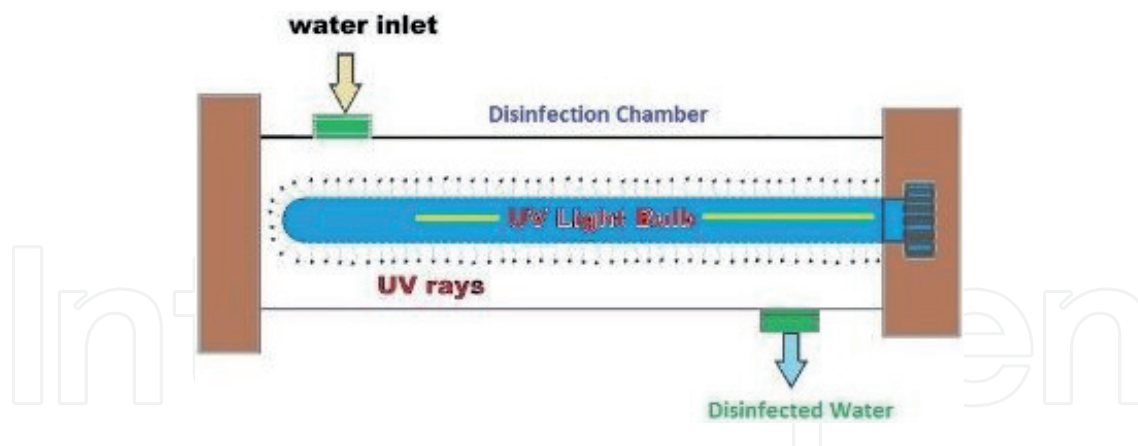
### 2.6.3. Process

UV disinfection units are used nowadays as water disinfection methods. The design is quite simple that consists of a UV light source that is enclosed in a transparent protective sleeve. The light source is mounted so that water can pass through a flow chamber so that UV rays can be both admitted and absorbed into the stream. No change in taste and color occur that is an advantage of this method. The contact time is also very short as these rays kill the pathogenic bacteria quickly [1].

### 2.6.4. Equipment

UV disinfection systems should be properly shut down if the treatment is not needed for few days. The lamp needs to be warm-up for few minutes before turning on. Moreover, the plumbing system should be properly flushed when not in use. The whole plumbing system should be disinfected by a chemical (preferably chlorine) before relying on the process.

UV lights loses effectiveness with usage, the lamp should, therefore be properly cleaned on regular basis and replaced once in a year. It should be noted that a new lamp might lose its



**Figure 5.** Disinfection by UV.

20% intensity in the first 100 h of operation. Properly calibrated UV detectors help the owner in alerting when the light intensity falls below a certain level.

The UV-treated water must be monitored regularly for the presence of heterotrophic bacteria and coliform bacteria monthly (first 6 months of device's use). The lamp's intensity should be checked if such organisms are noticed [16].

### 2.6.5. Chemical

UV light can treat water without producing any major chemical or physical changes in the water. No negative effects have been noticed in utilizing UV-treated water. Fewer chances are there for the formation of DBPs as no new substance is added in this process. No change in the taste and color occurs. The dosage and frequency used for the disinfection do not produce any harmful substance. Even the overdosing of UV light does not lead to the formation of harmful products. To avoid exposure, protective clothing should be used by the operator [7] (**Figure 5**).

## 2.7. Photocatalytic disinfection

The acceleration of a photoreaction in the presence of a catalyst is referred as photocatalysis. In catalyzed photolysis, adsorbed substrate is used to absorb light. In photogenerated catalysis, electron-hole pairs are created by the photocatalytic activity (PCA) generating free radicals (e.g., hydroxyl radicals:  $\bullet\text{OH}$ ) that have the ability to undergo secondary reactions. Its practical application was made possible by the discovering the electrolysis of water by using of titanium dioxide.

### 2.7.1. Advantages

The followings are the advantages of photocatalytic disinfection

- Photocatalysis uses capacity for renewable and pollution-free solar energy, thus it is a good replacement for the energy-intensive conventional treatment methods.

- In comparison to the conventional treatment methods photocatalysis leads to the formation of harmless compounds.
- Waste water contains different hazardous compounds. Photocatalytic process causes destruction of a wide range of these hazardous compounds in various wastewater streams.
- These reactions are mild. Less chemical input is required and the reaction time is modest.
- It can be applied to hydrogen generation, gaseous phase, and aqueous treatments as well for solid (soil) phase treatments to some extent [17].

### 2.7.2. Limitations

For the effective  $\text{TiO}_2$  application in water treatment, the mass transfer limitation has to be minimized since photocatalytic degradation mainly occurs on the surface of  $\text{TiO}_2$ .  $\text{TiO}_2$  has poor affinity toward organic pollutants (more specifically the hydrophobic organic pollutants) so the adsorption of organic pollutants on the surface of  $\text{TiO}_2$  is low that results in slow photocatalytic degradation rates. Therefore, targeting pollutants around the  $\text{TiO}_2$  nanoparticles to enhance photocatalytic efficiency require consideration. Besides this, the  $\text{TiO}_2$  nanoparticles may undergo aggregation due to the instability of the nanosized particle, which may hamper the light incidence on the active centers and consequently reduction in the catalytic activity occur. However, it should be noted that it may well happen that small particles show higher scattering, which can reduce their photocatalytic activity compared to larger ones. Furthermore, for the slurry system, one main practical challenge to overcome is to recover the nanosized  $\text{TiO}_2$  particles from the treated water in regards to both the economic concern and safety concern.

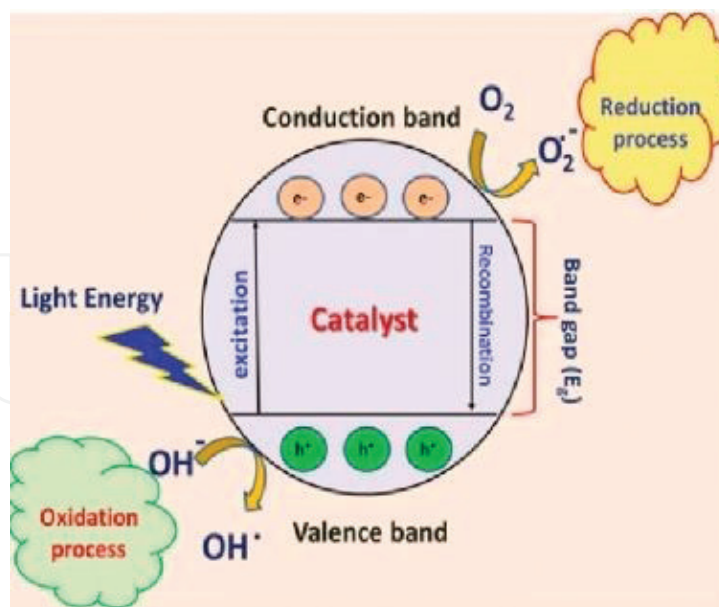
To overcome those limitations of  $\text{TiO}_2$ -based photocatalysis, the following countermeasures have been adopted in previous studies:

1. Modification of  $\text{TiO}_2$  catalyst, in order to achieve the utilization of visible light.
2. The catalyst synthesis should be optimized to obtain catalysts with defined crystal structure, high affinity to various organic pollutants, and smaller particle size.
3. Development and designing of second generation of  $\text{TiO}_2$  catalyst, with high separation ability, which can be recovered and regenerated effectively.

The purpose of these modifications and developments is to improve photocatalytic efficiency, complete degradation of organic pollutants, improve visible light absorption, improve stability and reproducibility, and to improve recycle and reuse abilities of  $\text{TiO}_2$  [18].

### 2.7.3. Process

Photocatalytic reaction depends mainly on light (photon) energy or wavelength and the catalyst. Generally, semiconductors are used as catalysts. These materials function as sensitizers for the irradiation of light-stimulated redox process because of their electronic structure. They have a filled valence band and a vacant conduction band.



**Figure 6.** Schematic representation of semiconductor photocatalytic mechanism.

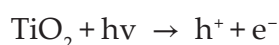
The fundamental steps in the process of semiconductor photocatalysis are as follows:

- When the light energy in terms of photons falls on the surface of a semiconductor and if the energy of incident ray is equivalent or more than the bandgap energy of the semiconductor, the valence band electrons move to the conduction band of the semiconductor.
- The valence band of semiconductors is left with holes. These holes can react with water molecules to generate hydroxyl radicals by oxidizing donor molecules.
- Superoxide ions are formed by reacting the conduction band electrons with dissolved oxygen species. These electrons induce the redox reactions.

These electrons and holes might undergo successive redox reactions with many species to form necessary products by absorbing on the surface of the semiconductor [19] (**Figure 6**).

#### 2.7.4. Chemical

TiO<sub>2</sub> is a semiconductive material that acts as a strong oxidizing agent during illumination by lowering the activation energy required for the decomposition of organic and inorganic compounds. The illumination of the surface of the TiO<sub>2</sub> induces two types of carrier separation: (1) an electron (e<sup>-</sup>) and (2) a hole (h<sup>+</sup>). For the production of these two carriers, sufficient amount of energy must be supplied by a photon to move an electron (e<sup>-</sup>) from the valence band to the conduction band, thus leaving a hole (h<sup>+</sup>) in the valence band. In comparison to the conducting materials, the recombination of holes and electrons is relatively slow in TiO<sub>2</sub> recombination in metals occurs immediately [20].





### 3. Conclusions

Water can be affected by environmental factors. Both human and environmental risks are taken into account, which may be tangible and/or intangible. Chlorination can lead to the formation of by-products or toxic chemicals that are hazardous to aquatic life. High chlorine residues may range from avoidance to death of aquatic organisms. The threshold tolerance limit of some aquatic species to chlorine is 0.002 mg/l in freshwater and 0.01 mg/l in saline water. The by-products can also accumulate in the aquatic environment. The toxicity of the chlorinated residues can be eliminated by dechlorination.

In summary, the beneficial use of aquatic ecosystem protection may be compromised when chlorinated wastewater is discharged to receiving surface waters.

Chlorination might not be a risk to the environment if the treated wastewater is reused beneficially rather than discharging into receiving surface waters. An acceptable method for disinfecting wastewater reuse is chlorination. Chlorination is the best method for reuse applications when a residual is required for microbial re-growth. However, there is a limitation of 1 mg/l of chlorine at the point of application of reclaimed water. These limits mostly do not harm the plant life. However, some sensitive crops may be damaged at a level of chlorine lower than 1 mg/l and users should consider the sensitivity of any crops that may be irrigated with chlorine disinfected reclaimed water. However, little environmental risks are associated with the direct use of chlorine. However, the manufacture, storage, and transportation of chlorine products still pose a risk to the environment.

Toxic by-products are formed by the oxidation of ozone. Ozone gas might harm the environment because of its corrosive nature.

Microfiltration only poses a risk to the environment if there is a spill of cleaning agents or the contaminated backwash waste is disposed of incorrectly. UV light poses less risk as compared to other disinfection methods, but it may pose a risk regarding photo-reactivation and mutation of the microbial population present in the discharge. No reuse option is available for UV lamps. Controlling the natural systems like detention lagoons is difficult.

A major environmental risk associated with lagoon-based disinfection is the excessive growth of undesirable organisms, such as blue-green algae. Humans are at high risk as blue-green algal blooms produces toxins. Environment is also at risk as the levels of SS and BOD increases. In terms of potential environmental cost, it would appear that UV, lagoons, and microfiltration have the least potential to impact adversely upon the environment, followed by ozonation and then chlorination. This ranking is based on the formation of by-products and the level of toxicity of the discharge to the receiving environment.

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