Chapter

Emerging Technologies in Water Treatment: Recent Advances

Carlos Martín Enríquez Castro, Manuel Pérez Nafarrate, Anuar Manuel Badillo Olvera and César Guzmán Martínez

Abstract

Ozone, a triatomic oxygen molecule, is a powerful oxidant generated by water electrolysis or produced in situ using the corona discharge method. Typical applications in water treatment involve the disinfection, disposal of virus, bacteria, and hydrogen sulfide removal and are responsible for odorous compounds in septage tanks and oxidation lagoons. Recently, electrocoagulation and cavitation have evolved to increase the efficiency of ozone gas disinfection. Electrocoagulation (EC) permits the sanitation of wastewater, the destruction of oil-water emulsions, and heavy metals present in mining waste and manufacturing industry. EC is useful when traditional disinfection methods using chemical agents or biological treatment is not completely efficient. Using the EC technology proposed by Reingeniería en Saneamiento Ltd., replacement of sacrifice electrodes is not estimated. Cavitation and ozone systems, as beneficial processes in water treatment technology are supported by electroflotation, electrocoagulation, and electrochemistry in urban wastewater plants to accomplish effective solutions in different processes. Along with the chapter, how modular plants can be designed to achieve the correct purification system based on a previous diagnosis of the process is explained. Finally, due to complexity of treatment process, automation need to advance from manual control to programmable logic controllers if control architectures for water treatment system advance in the same way the depuration process is properly controlled.

Keywords: ozone, electrolysis, electrocoagulation, cavitation, water treatment

1. Introduction

Ozone is a natural gas created from oxygen atoms. The oxygen molecule is made up of two oxygen atoms. These oxygen molecules are broken into atoms by corona discharge during electrical storms or by UV light from the Sun [1]. Individual oxygen atoms cannot exist alone without reassembling back into diatomic oxygen molecules. During this recombination step, some atoms will regroup into loosely bound triatomic oxygen. This new molecule is called ozone, ozone is a very strong oxidant and an ideal chemical-free purification and disinfectant agent. Ozone is often misdiagnosed as low-altitude pollution [2]. This could not be farther from the truth. In fact, ozone breaks down pollutants and should be welcomed when it is in the air. The most effective way to produce ozone commercially is through the use of corona discharge [3].

Ozone is dissolved thirteen times faster in water than oxygen and acts immediately, instead of using chlorine. Several functions such as dispatch of viruses, bacteria, molds, spores, and algae make this chemical agent very efficient [4]. Plenty of applications in the industry and home are extensive: ozone oxidizes nitrites to nitrates, organic nutrients and hydrogen sulfide are dissolved, color and odor are vanished, BOD can decrease, and dissolved oxygen is increased. Nowadays, it can be inferred that water treatment is the most beneficial.

1.1 How does ozone work?

When ozone is exposed to a bacteria or a virus, it immediately destroys the cell membrane. This happens in less than a second. Ozone is an oxidizing agent and when it encounters any odor molecule, oxidation occurs (chemical combustion) as shown in **Figure 1**. Disinfection by triatomic oxygen (ozone) occurs through the rupture of the cell wall. This is a more efficient method than chlorine, which relies on diffusion into cell protoplasm and inactivation of enzymes. An ozone level of 0.4 ppm for four minutes has been shown to kill any bacteria, viruses, mold, and mildew. When the effectiveness of ozone as a disinfectant was measured, there was little or no disinfection up to a certain dose. At higher levels, the disinfectant effect increases. For complete disinfection, excess or residual ozone must be maintained in the solution to ensure that all living microorganisms have been contacted. No antibiotic that is really effective in the field of virus has been discovered yet. There are indications that DNA viruses such as herpes are implicated in human cancers, as they organize the host cell's genetic material to produce new viruses. Ozone will inactivate viruses on contact, even at very low temperatures and residual concentrations. In the case of polio, just 0.012 ppm kills all viral cells in less than 10 seconds. Mold and mildew are easily controlled by the ozone present in the air and in the water. Giardia and Cryptosporidium cysts are susceptible to ozone but are not affected by normal chlorine levels.

As can be seen in **Figure 2**, ozone reacts with a bacterium, and a cracking process inside the cell structure is initiated [1]. Ozone penetrates into the periphery of the cell wall [2]. The ozone penetrates and creates a hole in the bacterial wall [3]. The ozone molecule in the bacterial cell structure is inserted [4]. Magnification of the bacterial cell after contact with the ozone molecules [5]. Destruction of the cell after ozone

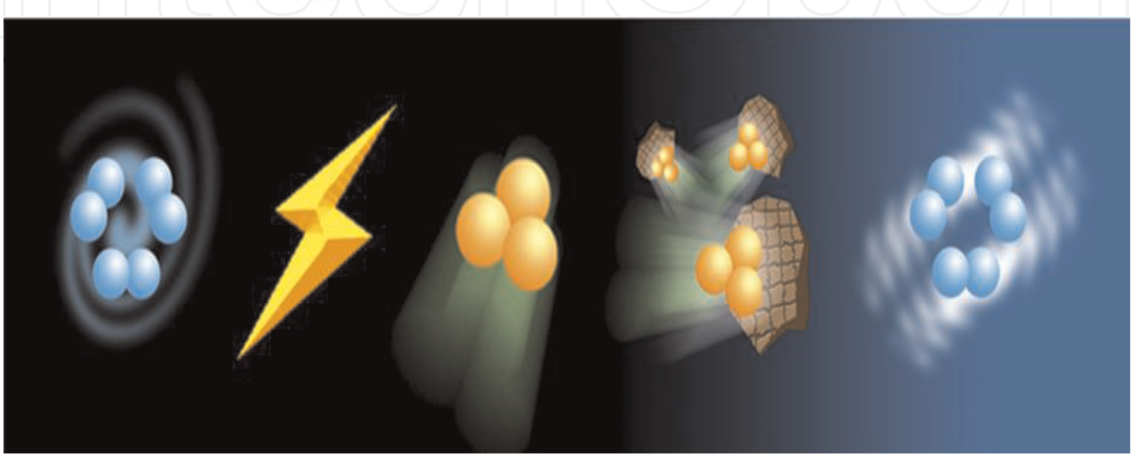

Figure 1.
Mechanism of ozone in touch with an electric source to produce pure oxygen. (adapted from www.ozonesolutions.com).

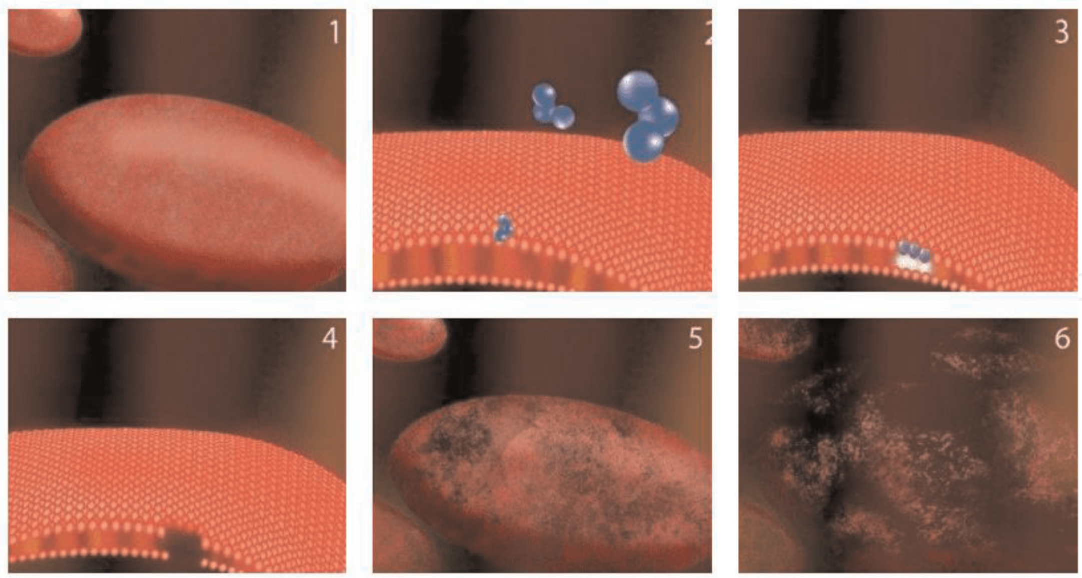

Figure 2.
Detail of ozone action in the bacterial cell. https://my.medklinn.com/knowledge_centre/effect-of-ozone-on-bacteria/.

action. Research investigations to destroy gram-negative and gram-positive bacteria's have been conducted [2, 3, 5]. A procedure to destroy enterobacterias such as *E. coli* at 95°F, using ozone, requires an ozone range between 0.1 and 0.5 mg/l and maintaining an adequate redox potential to reach a higher disinfection efficiency [6].

The mechanisms of ozone bacterial destruction need to be further elucidated. It is known that the cell enveloped by bacteria are made of polysaccharides and proteins and that in Gram-negative microorganisms, fatty acid alkyl chains and helical lipoproteins are present. In acid-fast bacteria, such as *Mycobacterium tuberculosis*, on third to one-half of the capsule is formed of complex lipids (esterified mycolic acid, in addition to normal fatty acids), and glycolipids (sulfolipids, lipopolysaccharides, mycosides, and trehalose mycolates). The high lipid content of the cell walls of these ubiquitous bacteria may explain their sensitivity, and eventual demise, subsequent to ozone exposure. Ozone may also penetrate the cellular envelope, directly affecting cytoplasmic integrity, and disrupting any one of numerous levels of its metabolic complexities.

1.2 Characteristics of ozone as a disinfectant agent

The effect of ozone to eliminate pathogens has been corroborated for several decades. Its killing action on bacteria, viruses, fungi, and many species of protozoa serves as the basis for its growing use in disinfecting municipal water supplies in cities around the world. Bacteria are microscopic so-called tiny single-celled creatures that have a primitive structure. They absorb food and release metabolic products, and multiply by division. The body of the bacterium is sealed by a relatively solid cell membrane. Their life processes are controlled by a complex enzyme system. Ozone interferes with the metabolism of bacterial cells, most likely by inhibiting and blocking the functioning of the enzyme control system. A sufficient amount of ozone passes through the cell membrane, and this leads to the destruction of bacteria. Viruses are small, self-contained particles built of crystals and macromolecules. Unlike bacteria, they multiply only within the host cell. Ozone destroys viruses by diffusing through the protein coat in the nucleic acid core, resulting in viral RNA damage. At higher concentrations, ozone destroys the capsid or outer protein shell by oxidation. Indicator bacteria in effluents, namely coliforms and pathogens, such as *Salmonella*, show a marked sensitivity to ozone inactivity. Other bacterial microorganisms susceptible to the disinfecting properties of ozone include *Streptococci, Shigella, Legionella pneumophila, Pseudomonas aerunginosa, Yersinia enterocolitica, Campylobacter jejuni, Mycobacteria, Klebsiella pneumonia*, and *Escherichia coli* [1]. Ozone destroys both aerobic and, more importantly, anaerobic bacteria, which are primarily responsible for the devastating sequelae of complicated infections, as exemplified by pressure ulcers and gangrene.

Ozone is the most oxidizing agent available to man after fluorine. Thanks to its high oxidizing power, ozone is capable of attacking and destroying all kinds of microorganisms such as bacteria, cysts, virus, algae, spores, and protozoa. Several research papers talking about the importance of these topics have been realized previously [1, 7–10]. Ozone used in combination with other emergent technologies decomposes organic substances including detergents, phenols, pesticides, herbicides, and fertilizers; neutralizes inorganic substances such as ammonia, urea, nitrites, cyanides, and arsenic [11]. Numerous families of viruses including poliovirus I and II, human rotaviruses, Norwalk virus, Parvoviruses, and hepatitis A and B, among many others, are susceptible to the virucidal actions of ozone. Most research efforts on virucidal effects of ozone have centered upon ozone's propensity to break apart lipid molecules at sites of multiple bond configuration. Indeed, once the lipid envelope of the virus is fragmented, its DNA or RNA core cannot survive. Non-enveloped viruses (Adenoviridae, Picornaviridae, namely poliovirus, Coxsackie, echovirus, rhinovirus, hepatitis A and E, and Reoviridae (Rotavirus)), have also begun to be studied. Viruses that do not have an envelope are called "naked viruses." They are constituted of a nucleic acid core (made of DNA or RNA) and a nucleic acid coat, or capsid, made of protein. Ozone, however, aside from its well-recognized action upon unsaturated lipids, can also interact with certain proteins and their constituents, namely amino acids. Indeed, when ozone comes in contact with capsid proteins, protein hydroxides and protein hydroxides and protein hydroperoxides are formed.

Viruses have no protection against oxidative stress. Normal mammalian cells, on the other hand, possess complex systems of enzymes (i.e., superoxide dismutase, catalase, and peroxidase) that tend to ward off the nefarious effects of free radical species and oxidative challenge. It may thus be possible to treat infected tissues with ozone, respecting the homeostasis derived from their natural defenses, while neutralizing offending and attacking pathogens devoid of similar defenses. The enveloped viruses are usually more sensitive to physicochemical challenges than naked virions. Although ozone's effects upon unsaturated lipids are one of its best-documented biochemical action, ozone is known to interact with proteins, carbohydrates, and nucleic acids. This becomes especially relevant when ozone inactivation of non-enveloped virions is considered. Fungi families inhibited and destroyed by exposure to ozone include *Candida, Aspergillus, Histoplasma, Actinomycoses*, and *Cryptococcus*. The walls of fungi are multilayered and are composed of approximately 80% carbohydrates and 10% of proteins and glycoproteins. The presence of many disulfide bonds had been noted, making this a possible site for oxidative inactivation by ozone. In all likelihood, however, ozone has the capacity to diffuse through the fungal wall into the organismic cytoplasm, thus disrupting cellular organelles. Protozoan microorganisms disrupted by ozone include *Giardia, Cryptosporidium*, and free-living amoebas, namely *Acanthamoeba, Hartmonella*, and *Naegleria*. The antiprotozoal action has yet to be elucidated.

DOI: http://dx.doi.org/10.5772/intechopen.109063

2. Effect of ozone in the treatment of industrial effluents

According to Ostman et al. [12], to reach the scale-up of an adequate ozone treatment system, the following considerations are important: accomplishing the demand for ozone and considering the flow rate on demand, design, and development of all the peripheral equipment necessary to maintain the production process including the ozone generator, pipes and reaction chamber, and the panel control considered can include the instrumentation devices and power unit. Reingeniería en Saneamiento Ambiental Ltd. has evolved in technology transfer offering its products with an uninterrupted improvement philosophy. To increase in the demand for ozone, the concept of modular plants provided in their business proposals is considered. Another point in the prototype design is to recall the primary purpose of the model. In **Figure 3**, it is displayed a specific model to comply with the specifications of the construction industry.

According to the operational principle of the TRIO3® injector, when pressurized operating water enters the interior of the injector, it is compressed in the injection chamber and changes into a high-velocity jet of water. The increased velocity through the injection chamber results in a decrease in pressure, thus allowing gas (ozone or air) to be drawn through the suction port and entrained in the water stream. As the water stream moves toward the injector outlet, its speed is reduced and it exits at a lower pressure than the injector inlet pressure. TRIO3 has invented and manufactured an injector superior to anything on the market today. The size of the bubbles allows the ozone gas to have full contact with the water and to control the release of the gas. The excellent mass transfer of this injector allows more "work" with less ozone, saving the customer money. As the ozone gas enters the water stream, it is in the form of small "micro-bubbles," which are aggressively mixed with the water. These "micro-

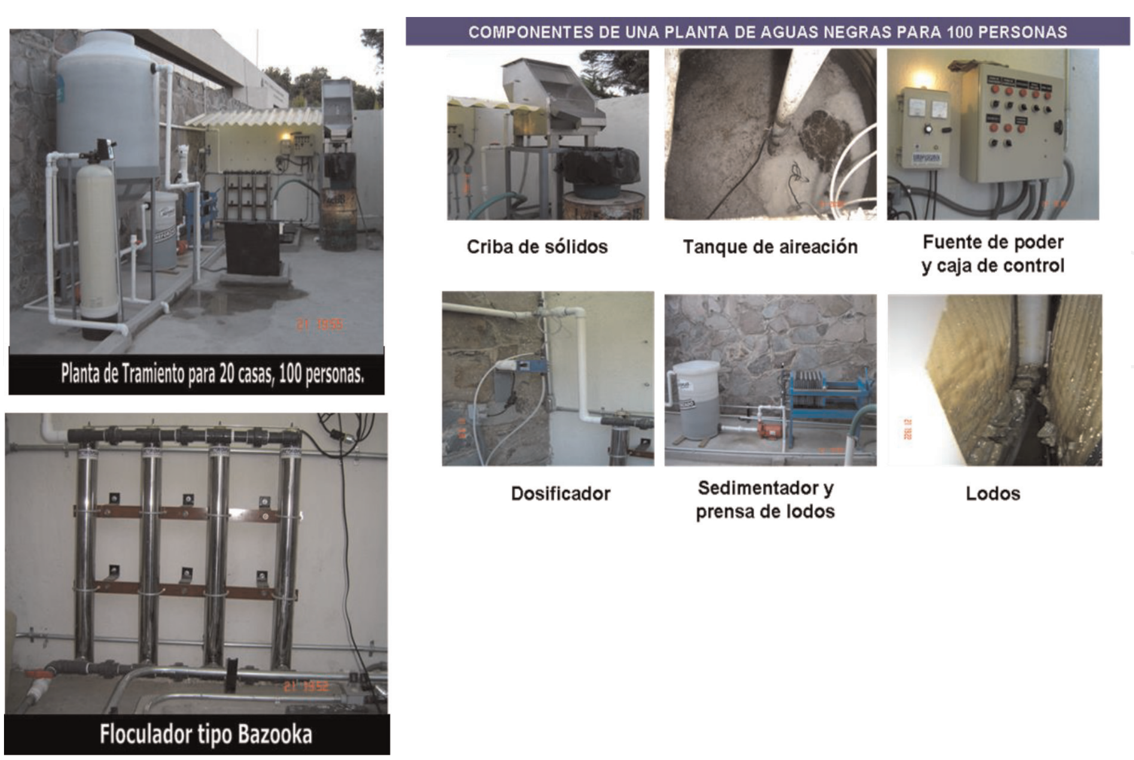

Figure 3.
Components of a water treatment plant for a housing complex of 20 houses and 100 inhabitants (with TRIO3 permitted authorization).

Time (min)	ppm*	% ozone
1	5.78	68
5	6.64	78
10	6.47	78

*Average concentration was 6.29 ppm.

Table 1.
Ozone concentration in the injector using microbubbles.

bubbles" provide an exceptionally large surface area on which ozone can be effectively transferred into the water. A large bubble is 20 mm and has a volume of 4.19 cm^3 and a surface area of 12.6 cm^2. Two hundred and ninety-six small bubbles (3 mm) can be won instead of the big bubble in previous point with a total area of 3.6 cm^2. This is 6.6 times the area of the large bubble. This smaller bubble has better mass transfer, and the process becomes more efficient.

Table 1 shows the operating parameters using a TRIO3® injector. The measured dissolved oxygen concentration was a 150-gallon tank of water in the TRIO3® injector installed, using a baseline of 4.76 ppm and 56% of purity at 73.4°F. The oxygen concentrator uses air drawn from outside the housing through a Solberg replaceable element coarse particle air filter. The integral compressor passes air through a bed of molecular sieves providing 95 $\pm$1% pure oxygen feed gas through the ozone cell. Air passing through the filter is stripped of nitrogen and water vapor to give dry oxygen feed gas. The oxygen concentrator gives a true dew point of -52°C to prevent the formation of HNO_3 (nitric acid) within the ozone cell. Oxygen is regulated for pressure and flow and is set at 6 L/min introduced through stainless steel fittings and Teflon tubing into the ozone cell. The ozone cell is powered by solid-state electronics and is a medium-frequency generator designed to operate at 500 Hz and 50,000 V. In this way, oxygen passing through the ozone cell is converted into ozone. Ozone exits the cell through a stainless steel and ozone-proof line to a stainless steel bulkhead that fits into the bottom of the housing and connects to the blower assembly.

2.1 Ozone as a disinfectant agent in municipal waste effluents

Hydrogen sulfide (H_2S), an acutely toxic substance, is immediately lethal at relatively low concentrations. H_2S becomes a health and safety hazard when it combines with carbon dioxide and water vapors as it corrodes plant equipment and piping. When shaken it erupts with such speed that levels of toxicity paralyze the lungs. This eruption occurs when stagnant sewage is shaken by loosening a plug. Wastewater contains up to 6000 ppm. Exposures as low as 300 ppm over a 30 min period will render a person unconscious. Exposure to a concentration of 1000 ppm of H2S in air causes paralysis of the respiratory system, cardiac arrest, and death within minutes. H2S is produced by the action of anaerobic sulfur-fixing bacteria on materials containing sulfur. In low concentrations, hydrogen sulfide smells like rotten eggs. At high concentrations, it desensitizes the sense of smell, and in the nose, it is no longer detectable. H2S is colorless, flammable, heavier than air, soluble in water, and extremely toxic.

Research conducted by the National Institute for Occupational Safety and Health (NIOSH) at three municipal wastewater treatment plants resulted in worker health symptoms of shortness of breath, sore throat, eye irritation, nausea, and diarrhea. Area air samples were collected for H_2S using sensor monitors and data loggers. Hydrogen sulfide concentrations ranged from undetectable to 124 ppm. NIOSH recommended exposure limits for hydrogen sulfide are capped at 10 ppm. This may not be exceeded during any part of the working day. As confirmed by OSHA regulations, 124 ppm H_2S exposure is immediately dangerous to life or health conditions.

Municipal waste effluents (MWE) are present mainly in a big populated city. MWE includes a combination of aromatic compounds, oily discharges, and food industry waste. MWE are hardly degradable by conventional methods, and due to high toxicity have high COD lectures [13]. MWE deposited in waste-activated sludges are oxidized using combined methods such as ozone and electrocoagulation [14, 15]. Next, a first case study was performed at the *Miami Dade County Water and Sewer Department* (WASD) and applied in a Corrosion Control Program to implement the inspection and assessment of several pumping stations of potable water.

2.1.1 Introduction

Identifying and rehabilitating corrosion deterioration in the pump stations of WASD. As part of WASD's corrosion control program, technical personnel inspected approximately 34 pump stations for corrosion damage in recent years under two different projects. As an additional WASD staff performing routine maintenance, 18 pump stations with significant corrosion were also identified. This project provided engineering services for a corrosion inspection and evaluation of the 52 pumping stations. The findings and recommendations are presented in this report.

2.1.2 Objective

The objective of this project was to identify the necessary rehabilitation efforts to repair existing damage and mitigate further corrosion deterioration of each of the pumping stations. A prioritized schedule and preliminary cost estimate for the implementation of recommended corrective actions were also provided.

The realization of this project involved the following tasks:

1. Inspect all pump stations identified by WASD.

2. Evaluate the extent of corrosion based on the inspection results.

3. Identify the necessary measures of rehabilitation and protection against corrosion.

4. Develop cost estimates at the planning level.

5. Prepare a prioritized schedule for implementation.

6. Prepare a report documenting the inspection findings and recommendations.

2.2 Inspection

During the inspections, the extent of the corrosion was documented through photographs. Due to H_2S levels, inspections often included confined space entry procedures, including self-contained breathing apparatus (SCBA). Once the pumping stations were entered, specific assessments of the condition of the station were made, including:

1. The severity of structural corrosion (lack of concrete and exposed rebar).

2. The state of gates, handrails, ventilation, and lighting.

3. The corrosivity of the atmosphere (levels of hydrogen sulfide).

2.2.1 Selection of pumping stations

The selection of the pumping stations, which were inspected as part of this study, was based on the following:

1. An initial list of significant corrosion damage in pump stations identified by the WASD Pump Station Division.

2. Subsequent inspections by the WASD team revealed additional pumping stations with more severe levels of corrosion.

3. Pumping stations identified by the staff crew with significant corrosion damage in the framework were classified in the "Pumping Station Odor Survey Project."

4. The pumping stations inspected under this project are those believed to have the most severe corrosion problems based on available information.

2.2.2 Other considerations

The pump station dry well was also inspected for conditions that could contribute to corrosion. Items of concern included:

1. The general condition of the structure of the dry well, pumps, and electrical components.

2. Suction or discharge ventilation.

3. If a dehumidifier is present and working.

4. If a sump pump is present and working.

5. Some of the criteria that were evaluated included the Corrosion Description (None, Not Remarkable, Apparent Corrosion) and the Corrosion Classification (Depending on the white deposits caused by salts and minerals as well as the damage caused in the structure). **Figure 4** shows a detailed description of the pumping equipment damaged.

The findings of this investigation show that each pumping station presented different levels of deterioration. Even though none of the pumping stations inspected showed significant corrosion in the dry well, it was noted that a dehumidifier was

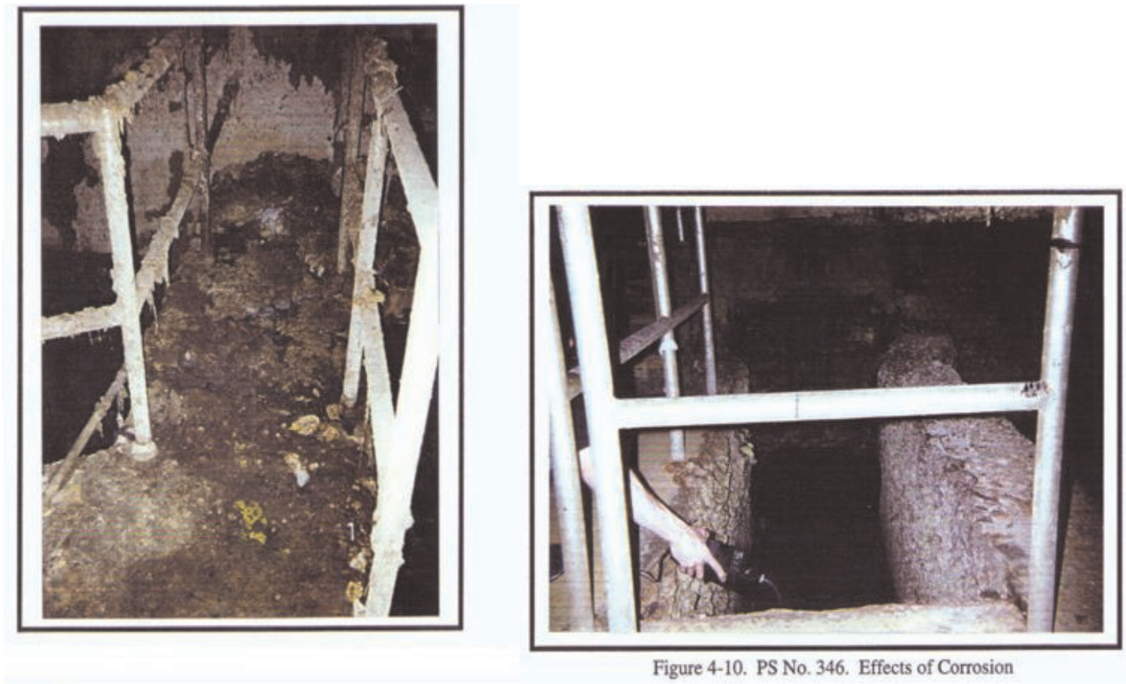

Figure 4.
Effects of corrosion in pumping stations (WASD Pump Station division permission).

required, which is essential to remove moisture and prevent a corrosive atmosphere in the dry well. In this way, it was possible to reduce this problem. On the other hand, the levels of hydrogen sulfide were monitored to know the aggressiveness of the atmosphere and the speed at which corrosion occurs inside the wet well. Severe corrosion damage can be expected at stations with levels between 1 and 10 ppm. Therefore, these data in combination with physical evidence provide a reasonable basis for determining the corrosion potential at each station. For example, some stations (PS 44 and PS 516) with moderate corrosion damage recorded hydrogen sulfide levels below 1 ppm on the day of inspection, a moderate level of corrosion, and loss of concrete from the walls, which indicates that these concentrations damage the structure of the pumping equipment due to the effect of the gas. The ozone, used at several concentrations (1, 3, and 5%) allowed the elimination of hydrogen sulfide, taking into account the safety problems that this represented. Regarding this point, it is convenient to point out that the entrance of personnel to the wet well is necessary for many pumping stations to carry out routine maintenance operations, such as cleaning of the bar screens, operation of the gate, and maintenance of pressure sensors.

Wet well level and pump suction bells. The safety of operations and maintenance personnel while performing these tasks was a primary concern in the wet well evaluation. The safety of each pump station was assessed based on the condition of the access ladder, work platform, handrails, and wet vent. Repair or replacement of any of the above. **Figure 5** shows the ozone generator used in the experiment.

The second case was developed in Gifford Florida, a facility that TRIO3 had installed and used to demonstrate the effectiveness of removing the odors from a wastewater treatment plant (WWTP). A proposal was suggested to the directive staff of the WWTP to eliminate odors with ozone at a reasonable cost in a 30-day trial.

Two units to prove the ability of ozone were mounted, and a month later three more systems were installed. A main disinfection objective in the workers' office allowed them to work in a clean and odor-free room. The other two were larger units

Figure 5.
Ozone generator (gas bust 2000 displayed with TRIO3 permitted authorization).

installed on the septage tank and in the dewatering building. On the facility, on a daily basis, were taken readings of the hydrogen sulfide levels. During these readings/tests, an MDS MINI responder hydrogen sulfide meter was used. The manual reading in the septage tank is shown in **Figure 6**.

Lectures taken during the trial were between 130 and 700 ppm of hydrogen sulfide. A properly sized machine as quoted herein eliminated 100% of the hydrogen sulfide and methane. The proposed unit treated all five chambers in the septage tank. Since the hydrogen sulfide is the more powerful odor than the methane second, all odors from this area of the plant ceased. Based on the pilot study conducted, an estimation of the septage tank requirements required a Gas Buster unit (as shown previously in **Figure 5**) sufficient to provide a minimum of 10 pounds per day of ozone. **Figure 7** shows the detailed facility monitored.

The dewatering building is the source of several odorous compounds. Therefore, the removal of the liquids and the composition of the solids are a major source of odors. The chief culprit is again hydrogen sulfide. As treated sewage solids are

Figure 6.
Readings taken in Septage tank (with TRIO3 permitted authorization).

Figure 7.
Septage tank with a gas buster unit installed (with TRIO3 permitted authorization).

introduced to the belt press, the liquid in the solids are removed in this facility as shown below in **Figure 8**.

The proposal of the odor control study proposed by TRIO3 in the sludge thickener tanks was a major issue to aboard. Ozone control system in Florida facility included the design and installation of a cover for the tank and interfaced a gas buster system so as to provide a blanket of ozone between the cover and the sludge. The dome designed is shown in **Figure 9**. The reduced loading of the scrubbers with the ozone system enhanced their ability to remove all odors. The loading from the Septage Tanks was virtually zero and the loading from the Dewatering Building was also zero. The scrubber was installed with the addition of ozone to perform as designed.

Figure 8.
Belt press used to treat sewage solids (with TRIO3 permitted authorization).

Figure 9.
Sludge thickener facility (with TRIO3 permitted authorization).

2.3 Evolution of water treatment units with different purposes

One of the characteristics present in the process developed by Reingeniería en Saneamiento Ambiental Ltd. around the last 20 years includes the addition of operative modules in order to fulfill the requirements of the process. **Figure 10a** shows the module installed with ozone and electrochemical oxidation/precipitation unit, reactor tank with measurements of 90 cm width x 1.20 m height. **Figure 10b** displays a complete PLC console; this rack includes a flocculation tank, aeration tank, ozone generator, power supply, and PLC control display.

Ozone molecules reacting with the influent give different qualities of treated water, which can be reached when active compounds (free radicals) react with the polluted mixture of the influent [16]. Therefore, a high quality treated water depends on the concentration of ozone used in the oxidation process as shown in **Figure 11**.

3. Innovative technologies in water treatment

3.1 Electrocoagulation

Electrocoagulation (EC) allows the purification of wastewater that has a high content of salts. To carry out the physicochemical operation of electrolysis, it is necessary to dissolve the compounds by means of electrodes provided with iron or aluminum. Due to this electrolysis reaction of water, hydroxyl compounds are generated [17].

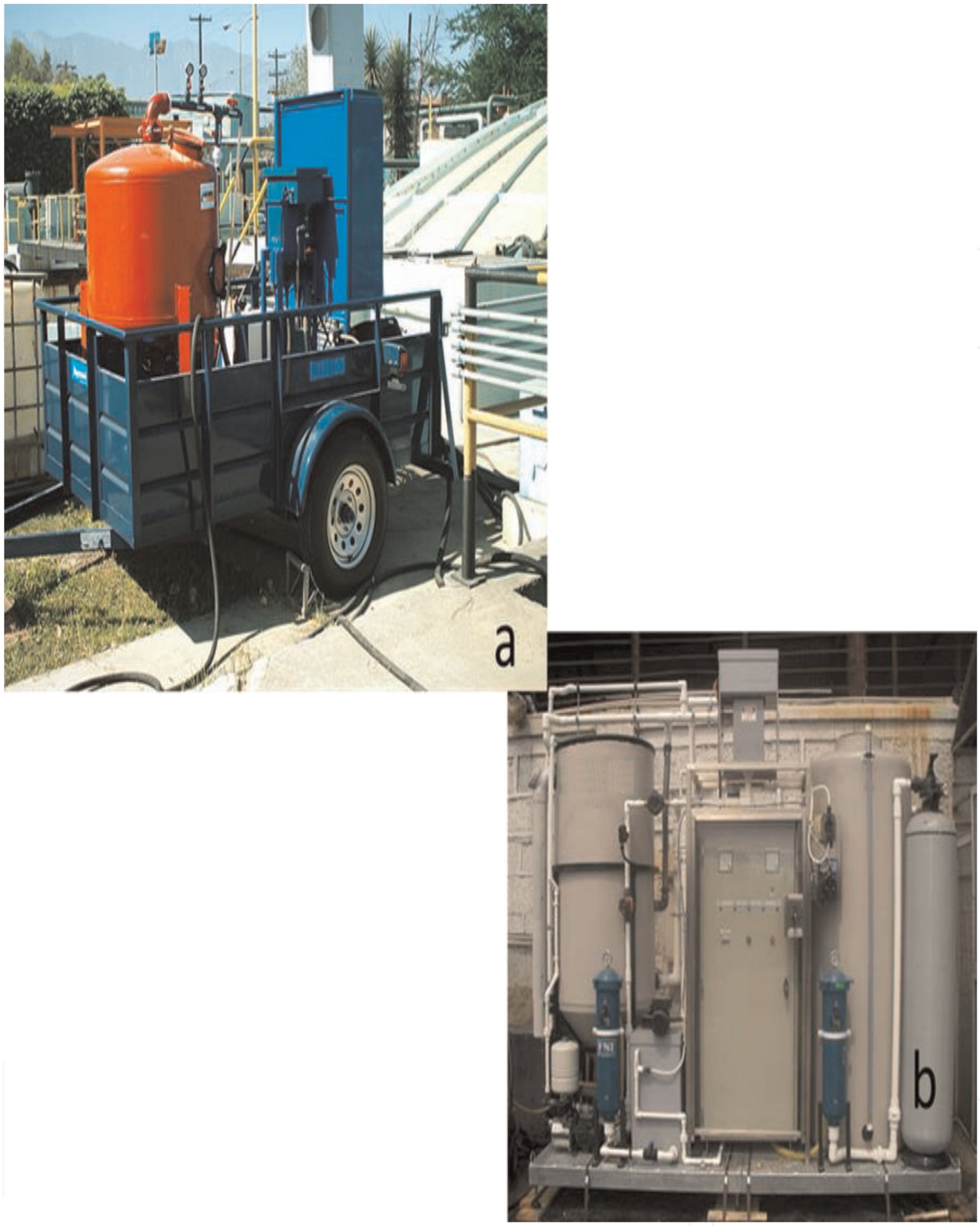

Figure 10.
Mobile unit provided with ozone generator and electrolysis unit (with TRIO3 permitted authorization).

According to Barrera-Diaz [18], EC is effective in the following processes:

1. Remotion of heavy metals such as oxides that pass the Toxicity Characteristic Leaching Procedure (TCLP).

2. EC eliminates successfully suspended and colloidal solids.

3. EC disrupts oil-in-water emulsions.

Figure 11.
Pictures of influent and the evolution in the quality of water for several effluent samples (with TRIO3 permitted authorization).

4. Separation of grease, oil, and lubricants.

5. Extraction and appropriate disposal of organic complexes.

6. EC remotion effectiveness of bacteria in an effective way.

7. Destruction of viruses and microorganisms.

Not many studies mention the EC and ozone to depurate wastewater at the industrial level, and most of the research developed under controlled conditions [11, 17]. Electrocoagulation is effective when we accomplish the following conditions: first, the device generates an electric charge between particles; the electrical layer between both particles must be strong enough to be repelled and prevent agglomeration. Finally, the flocculation capacity to form flocs is monitored. Flocs deposited at the bottom of the deposit are disposed of. Therefore, EC is possible when the process variables such as pH, impelling force, and aggregation level of the coagulant species are monitored correctly [18]. A detailed scheme of what happens in the EC process, as shown in **Figure 12**, is the following.

EC process is useful when the addition of chemical agents, such as chlorine, is not completely efficient as mentioned below:

1. The ions produced in excess during EC do not necessarily increase the number of salts in the influent avoiding a higher quantity of the sludge produced.

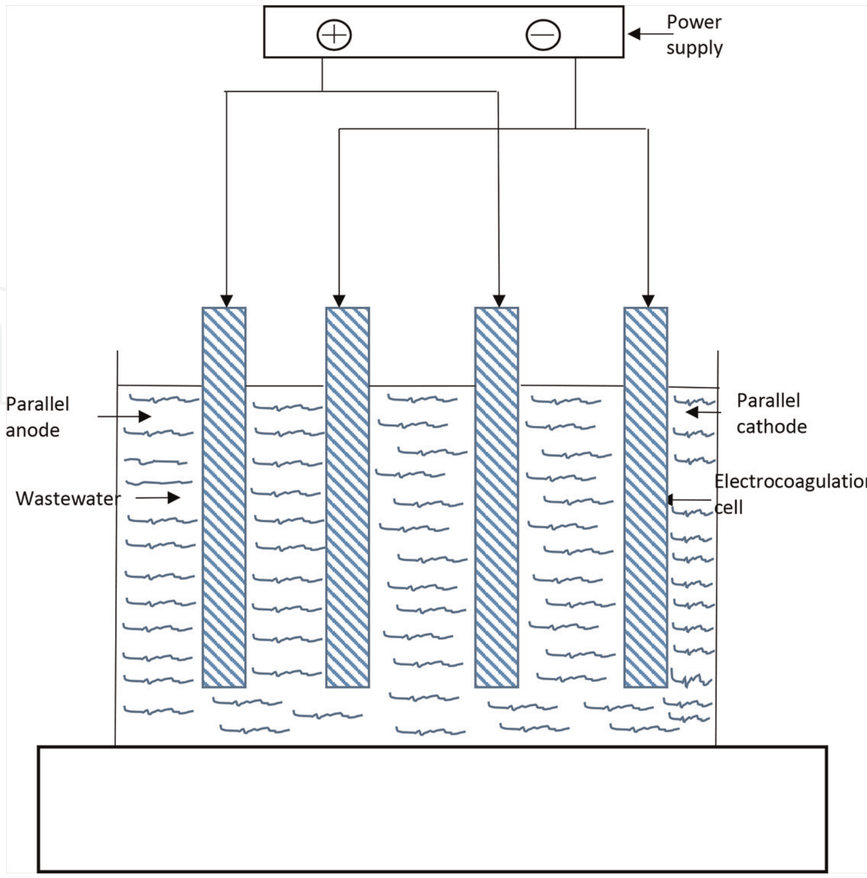

Figure 12.
Schematic design of electrocoagulation reactor (according to Mohammad Ahmadian design).

2. It is necessary to generate a higher electric activity to eliminate the contaminants effectively, removing them due to the generation of gas bubbles (H_2 and O_2) and dragging them to the surface.

3. A dissolved air flotation clarifier (DAF-type unit) line is installed to increase the flotation efficiency. In electroflocculation, the removal of contaminants is favored because the gas bubbles generated in the system (H_2 and O_2) drag them, so they tend to float on the surface.

The different variables involved induce three recurrent procedures but at the same time different from each other, as mentioned in Appendix 1. The theoretical foundation of electrocoagulation is that precipitation takes place at the same time as colloid destabilization. On the other hand, chemical coagulation consists of the formation of sludge due to the union of colloids, forming masses of considerable size, to later separate them from the water by adding more chemicals such as Aluminum Sulfate, Ferric Chloride, among others. The masses of colloids are formed by the contact between the colloids, this is achieved mainly by the movement of the liquid, due to electrical phenomena, such as the presence of ions of opposite charge to that of the colloids, action of hydrogens, and others. It is important to mention that the water is subjected to electrolysis, which is favored by the presence of dissolved salts, which enable the conduction of electricity and are present in all wastewater and industrial water. Due to this, a release of gaseous Hydrogen and Oxygen is produced in their respective electrodes. When these gases rise to the surface, they cause three phenomena: (1) Quick separation of colloids from the electrode, preventing it from getting

Energy consumption	Energy consumption varies (depending on the type of water to be treated).
Electrode wear	With our Technology, replacement of the electrodes is not estimated, since they are made of food grade 316 L stainless steel, so there is no wear on them, so it does not require washing the electrodes with acid to its descaling of salts
Operating conditions	The electrocoagulation system works automatically, through electronic controls that regulate current and voltage, according to changes in the quality of the wastewater to be treated, given by its resistivity.
Sludge production	The production or generation of sludge is directly related to the level of contamination of the residual water. In any case, the generation of sludge is less than a conventional chemical or biological system. A more compact sludge is obtained.

Table 2.
Process variables involved in electrocoagulation.

dirty (cleaning); (2) Dragging of destabilized colloids to the surface forming a cream, allowing not only extraction by classical sedimentation but also by flotation, and; (3) Due to the gas bubbles, ascending and descending currents of the solution are produced, causing a better contact surface, thus causing an increase in the destabilization efficiency. This "spontaneous" agitation avoids "mechanical" agitation (no external agitation needed).

Technical scope of electrocoagulation.

The electrocoagulation process can be defined as the destabilization of suspended or dissolved chemical species present in a solution, product of the application of an electrical potential difference through a cathode–anode system immersed in the water solution to be treated. As a consequence, and during the said electrolytic process, the cationic species produced at the anode enter the solution, reacting with the other species, forming flocs, and precipitating the respective hydroxides. Unlike chemical, coagulation is the origin of the coagulant.

Technical aspects of electrocoagulation operation.

The operating conditions of an electrocoagulation system are highly dependent on the chemical conditions, pH, particle size of the water to be treated, and especially its conductivity. The general treatment of wastewater requires low voltage applications (<50 Volts) with variable amperage, according to the chemical characteristics of the water. **Table 2** shows several technical aspects to consider when using electrocoagulation.

3.2 Comparative analysis of electrocoagulation vs. biological treatment

- The electrocoagulation system applied to wastewater, compared to conventional biological systems, requires a smaller surface (between 50 and 60% less).

- Electrocoagulation residence times are 10 to 60 s, compared to biological systems that require 12 to 24 h.

- They are compact units, easy to operate, with lower energy consumption and sludge production (more compact) than conventional biological systems.

- The electrocoagulation cells are made of PVC, or high-density polyethylene and are installed on the ground. Therefore, they do not require major civil works, such as chemical and biological systems.

- Investment costs are 50% lower than biological systems.
- Electricity consumption per m^3 of treated water, (between \$0.01 to \$0.05 USD/m^3), is less than conventional treatment systems.
- They do not use chemical products. They are 100% automatic units, which are used when required, with response times of 10 to 60 s, at their efficiency level.
- EC technology is adaptable to different types of Wastewater Treatment Plants.

Electrocoagulation is applied to the mining industry, electroplating, refineries, and foundries, among others. **Table 3** shows the percentage of removal of main parameters. More information about EC Technology parameters can be found in Appendix 2.

Parameter	% of remotion
Molibden	83–87
Arsénic	95–98
Aluminum	> 99
Barium	> 98
Calcium	96–99
Cadmium	> 98
Cobalt	60–65
Crome	> 99
Cupper	> 99
Iron	> 99
Magnesium	98–99
Manganesum	83–85
Níquel	> 99
Selenium	> 99
Valadium	95–98
Zinc	> 99
Suspended solids (turbidity)	> 95
BOD	> 90
COD	> 90
Oils and fats	> 95
Total Nitrogen	> 80
Total Phosphorus	> 70
Fecal Coliforms*	> 99% (*)

**Using ozone, at the outlet of the electrocoagulation treatment plant, an outlet concentration of <50 MPN/100 ml of Total Coliforms will be reached.*

Table 3.
Percentage of removal of main parameters.

3.3 Cavitation as a depurative process in water treatment technology

The cavitation, electrolysis, and ozone system does not require adjuvants in the treatment of wastewater. Hydro cavitation is a recently used technique that has benefited from technological advances in wastewater treatment and is the subject of multiple investigations. Cavitation uses concepts related to the characterization of the formation, growth, and subsequent collapse of activities that generate large amounts of energy, creating hot spots and strong oxidation conditions through the production of hydroxyl radicals [19]. According to Foster [10], cavitation, a phenomenon defined as nucleation, involves the growth and implosion of cavities filled with steam or gas, which are achieved by the passage of ultrasound (acoustic cavitation) or by changes in flow and pressure (hydrodynamic cavitation). To develop hydrodynamic cavitation is necessary to modify the geometry of the flow to increase the kinetic energy. The cavitation increases by having a construction of the flow that results in a considerable reduction of the local pressure of the liquid. This change in the pressure of the liquid increases the kinetic energy. Drops in the liquid pressure below its vapor pressure create millions of vapor cavities, and turbulent conditions of varying pressure fields downstream of the construction occur. The lifetime of these cavities is very short (a few microseconds). The cavities finally violently implode and generate high pressures (up to 1000 bar) and very high temperatures (10,000°K). These changes intensify chemical reactions and promote the formation of radicals and their subsequent reactions [10]. Extreme shear forces generated by cavitation events and shock waves help break down contaminant molecules, especially the complex high molecular weight compounds. The intermediate compounds are more prone to hydroxyl radical attack and biological oxidation, further enhancing the overall rate of degradation and the mineralization of wastewater. Under such extreme conditions, the water molecule inside the cavity becomes OH and H radicals. The OH radicals diffuse into the liquid and react with contaminant molecules, resulting in oxidation and mineralization products [20]. Applications of this proven technology have been mentioned in cold water [21], municipal sewage [13, 15], industrial wastewater [17], reuse of winery wastewater, artisan production of wastewater reuse, and any waste that requires removal of organic contaminants (PHC/PAH, dioxin/PCB, pesticides), COD/BOD and reductions in TSS [14]. A prototype adapted by TRIO3, as shown in **Figure 13**, displays the cavitation technology. The schematic diagram proposed by the company, mentioning components in **Figure 14**, complies with the technical

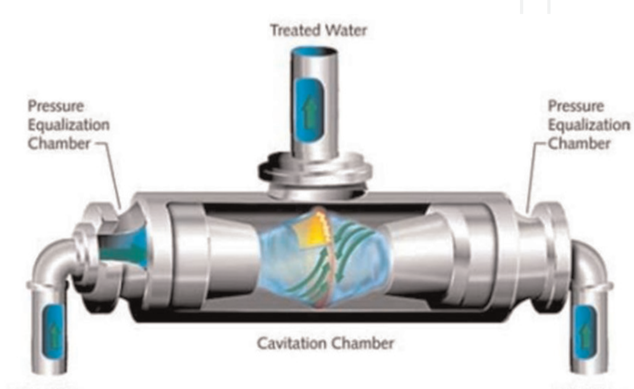

Figure 13.
Water treatment unit provided with cavitation technology (https://wcponline.com/2023/06/23).

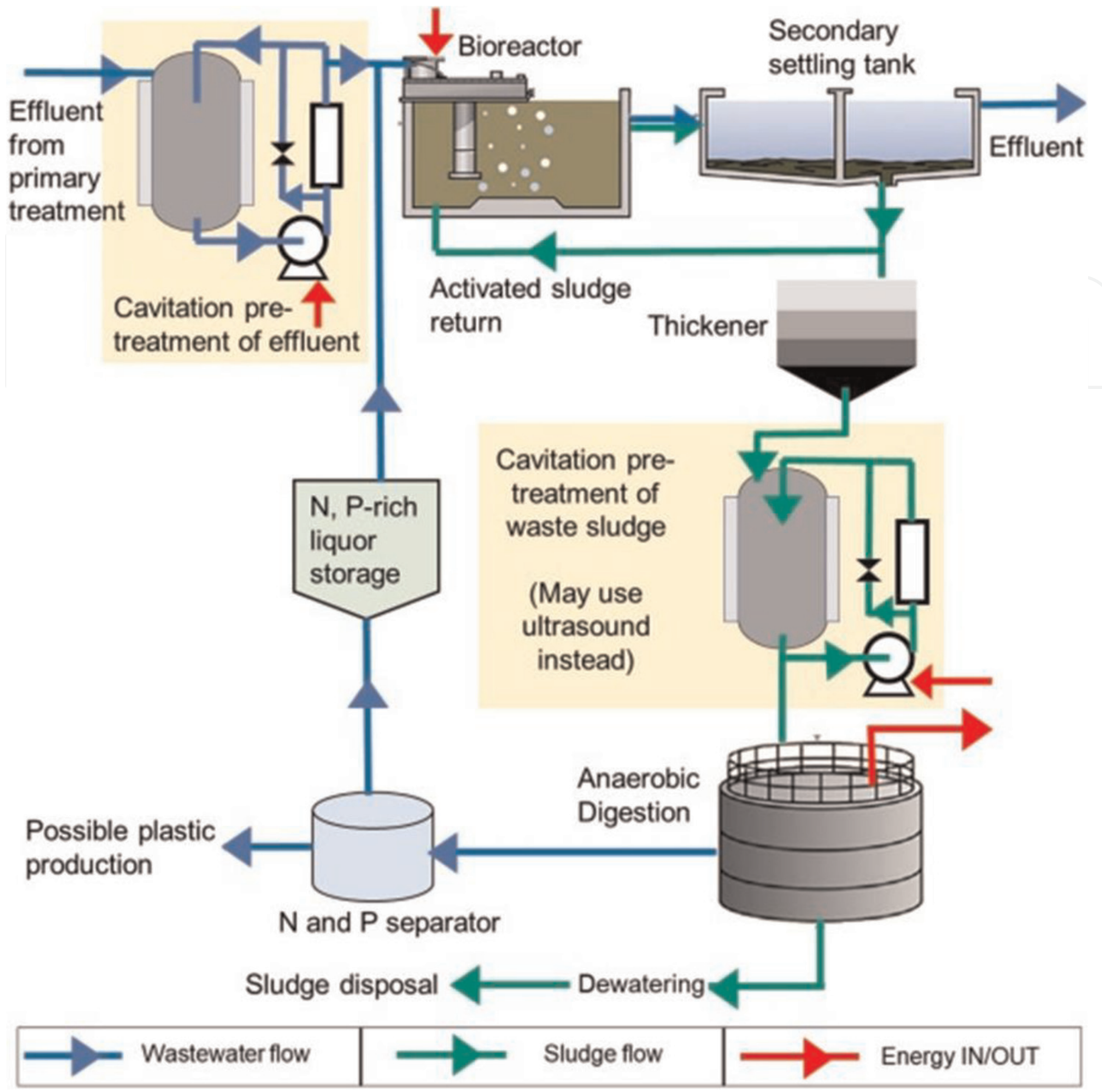

Figure 14.
Isometric diagram for a water treatment unit provided with cavitation technology. With permission of Bhat et al. (2021). https://www.sciencedirect.com/science/article/abs/pii.

Flow rate (l/s)	General dimensions		
	Length (m)	Width (m)	Height (m)
1.0–1.5	2.1	2.2	2.5
10	5	4	2.5
20	5	4	2.5
40	10	4	2.5
50	10	4	2.5

Table 4.
Specifications for the construction of hydro cavitation units.

specifications for water treatment procedures. According to the dimensions established in the equipment, the flow rate is dependent on these specifications as shown in **Table 4**.

The variables involved in **cavitation process** induce three common procedures but are different from each other [19]. These are: a) **electro-flotation,** where the gas to drag the contaminants previously conditioned to the surface is used, b) The **electrocoagulation-flotation** involves the injection of metal ions to agglutinate the pollutant agents dispersed in water, and directing them to the anode and sweeping the generated gas, and c) The **electrochemistry** operation involves redox reactions used to crack toxic compounds and treated later by biological procedures.

The process variables, above mentioned, relate to the type of contaminant to eliminate (see Appendix 2). Therefore, disinfection is due to anodic oxidation. Reingeniería en Saneamiento Ambiental Ltd. has made an effort to offer ecological Systems based on **Allotropic Physical Chemical Technology**. Through this ionization system, the molecules made up of two or more elements; dissociate the remaining molecules in their original state as atoms or ions. Thus, it softens the water, stabilizes the pH factor, and eliminates its encrusting capacity [7], as shown in **Figure 15**.

The urban wastewater treatment plant (WWTP) uses the process of technological innovation by electrolysis with photovoltaic energy and its construction process is with prefabricated PVC modules, which has the following advantages: quick installation by always having prefabricated parts in the warehouse, modular concept that allows future extensions, low cost of operation, low energy consumption, low sludge production, high system stability, easy operation, absence of unpleasant odors, and small area for installation. The dimensions of the proposed plant are based on the previously authorized final plans annexed to the WWTP contract and defining its scope. It is very important to note that, being a modular plant, the dimensions can be modified to adapt to the surface and geometry of the available land. The description of the proposed treatment process includes a plant with all the treatment units required to guarantee the correct purification of both wastewater and biological sludge, a product of the treatment process. The WWTP consists of a speed flocculation unit and an ionization unit. The treatment will be done in two phases; the first in a 15-min process of h**igh-speed flocculation** and the second in a 45-min phase of **high-impact ionization**, and final disinfection with ozone, with a capacity of 17.5 l/s for a period of 24 h, finally remaining for reuse. These are the main stages:

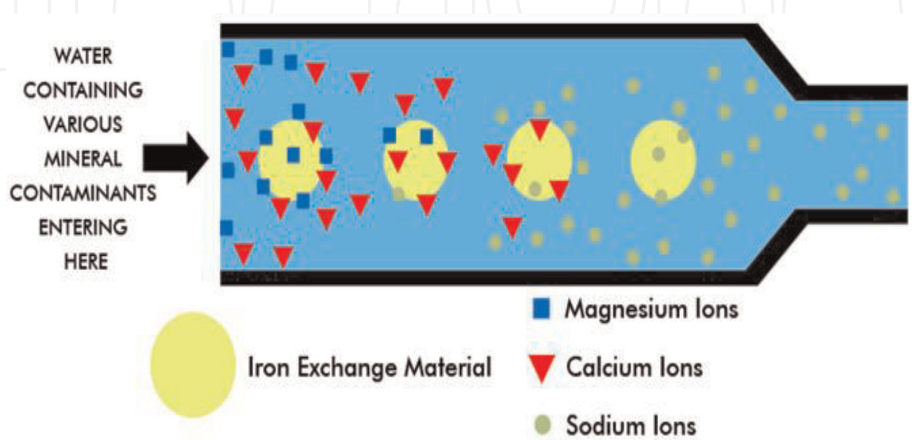

Figure 15.
Water deionization process. https://www.freedrinkingwater.com/water-education2/49-water-di-process.htm.

1. A screen is used for urban sewage to retain macro solids.

2. A regulator tank with a capacity of 45 m^3.

3. A sand trap with the capacity for the same flow.

4. High-speed flocculation unit. The system will be made up of 32 pieces of equipment, each consisting of four cathode electrodes 1¼" in diameter by 48″ length and two anode electrodes 1″ in diameter by 48″ length made of quality 316 stainless steel. Housed in eight tanks 1.50 m high by 1.00 m wide and 1.00 m length (1500 L each) made of hydraulic PVC schedule 40, with four equipment in each tank.

5. After the high-speed flocculation process, the water will pass to a hopper-type sedimentation tank, with a capacity of 14,000 L for separation of the sludge generated by this process and later passing to the sludge sump for disposal and the water to the system.

6. High-Impact Ionization Unit. The system will be made up of 96 pieces of equipment, each consisting of six cathode electrodes of 1¼" diameter by 48″ length and three anode electrodes of 3/4″ in diameter by 48″ long, made of quality 316 stainless steel. Housed in 24 tanks 1.50 m high by 1.00 m wide and 1.00 m long (1500 L each) made of hydraulic PVC schedule 40, depositing four teams in each.

7. Ozone Disinfection Reactor Tank Unit. The clarified and gauged water goes to the disinfection tank, which has a TriO3® brand Ozone system, in order to eliminate unwanted microorganisms and obtain treated water with the required quality. It has the function, as its name indicates, of disinfecting the water from pathogenic bacteria in humans, such as bacteria, viruses, and protozoa.

8. Sludge Digester. The excess sludge during the purification process is sent to the digester tank, where it is oxidized (a reduction of 40% of the volatile solids present in the sludge), since at this stage the microorganisms do not receive organic matter as food and they will only be provided with air (oxygen), promoting cannibalism (and at the same time avoiding the generation of odors) thus achieving a decrease in them, which will be ready for dehydration.

9. Sludge Drying Bed. The sludge previously stabilized in the digester and free of odors is sent to this equipment for drying, thus facilitating its handling and final disposal as a soil improver for green areas.

Because the WWTP proposed by TRIO3 is a modular type, the necessary modules can be increased according to the growth needs of the client. Following, **Figures 16** and **17** present a prototype of a WWTP using electroflocculation technology. **Figure 18** shows an oxidation lagoon and the disposal of treated water into the sea in the province of Santa Rosa Lambayeque, Peru.

Figure 16.
Picture of electroflocculation technology (copyright of Reingeniería en Saneamiento ltd).

4. Instruments and automation system in wastewater treatment process

In the last decades, the automation engineering of water treatment plants has presented advances that have led to improvements in the operation of the process [22]. For current plants, effective control is of critical importance, in terms of design, characteristics such as easy operation and maintenance and low operating cost are sought, as well as ensuring the capacity of the plant for the reduction or partial elimination of nutrients [23].

Due to the complexity of the treatment process, manual control of treatment plants may not provide the level of control necessary to meet all operating specifications. In this sense, in recent years with the rapid development of electronics, it is possible to use different devices such as Programmable Logic Controllers (PLCs), Industrial Computers, and Microcontrollers to carry out process control tasks automatically [24].

One of the most widely used control architectures for water treatment systems is SCADA (Supervisory Control and Data Acquisition) made up of different

Figure 17.
Picture of electroflocculation technology (copyright of Reingeniería en Saneamiento ltd).

Figure 18.
Oxidation lagoon and disposal of treated water in the district municipality of Santa Rosa Lambayeque, Peru (copyright of Reingeniería en Saneamiento ltd).

communication elements and human–machine interfaces, PLCs, remote terminals, and sensors. It is expected that this technology will soon be able to be adapted to the WTP technology to increase the productivity and automation of their processes. A human–machine interface (HMI) component is present within the SCADA tool, where human operators interact with the information acquired by the system through a browser interface, and also allows them to make decisions not programmed in the automatic system [25]. **Figure 19** illustrates the general architecture of an automated water treatment system.

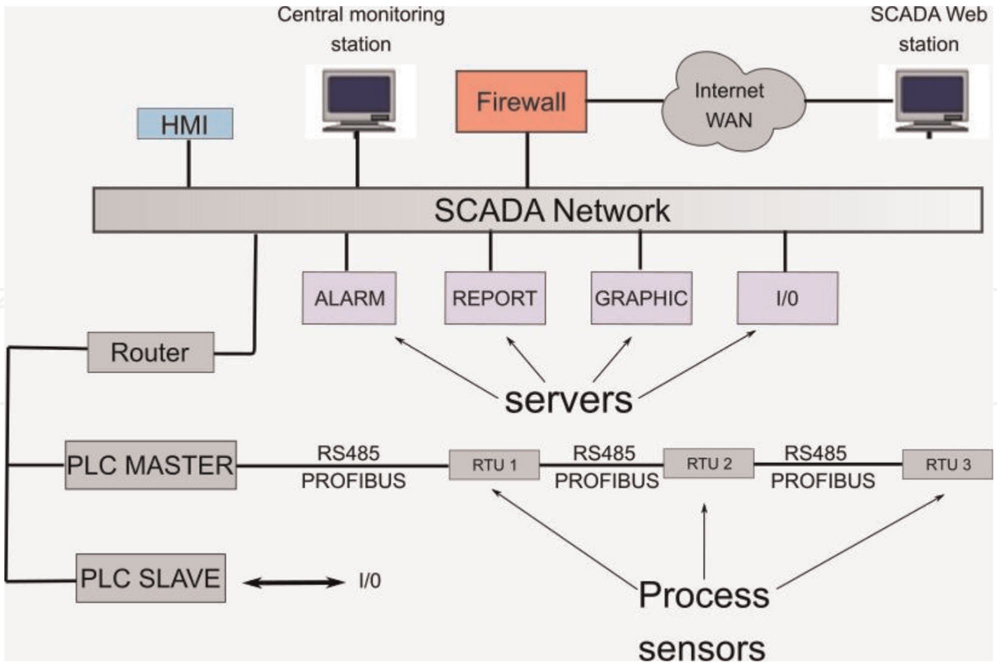

Figure 19.
SCADA hardware architecture for wastewater treatment plant. https://www.semanticscholar.org/paper/06/01/2023/Wastewater-treatment-plant-SCADA-application.

According to Wang [22], the following components can be considered as fundamental for the SCADA system:

- HMI (Human-Machine Interface). It presents human operators with the information acquired by the system through a browser interface, and also allows them to make decisions not programmed in the automatic system.

- Master unit of the SCADA system. It is in charge of acquiring the information collected by the remote stations and implementing the control law.

- RTUs (Remote Terminal Units). Automatically collects data and connects directly to process sensors. They function as slave units to the supervisory controllers or to the supervisory control and data acquisition (SCADA) master.

- PLC (Programmable Logic Controller). Used for automation of the wastewater treatment process and designed with multiple inputs and outputs. Its programming is in ladder language which is similar to electrical plans, which facilitates the interpretation of the code.

Additionally, the SCADA system has different sensors and transmitters which measure physical variables through different principles and convert them into physical signals for interpretation through the system. In general, PLCs are used in SCADA systems as process control elements, however, there are other alternatives such as Raspberry Pi boards, which can be more useful mainly for mobile treatment units (cavitation treatment) due to their size, energy consumption, and processing capacity [3, 26]. Raspberry Pi boards can be considered as microcomputers since they have a microprocessor that works under the ARM architecture and also has a series of digital I/O ports that allow acquiring the signal from the sensors and executing the control law through its Departures. The Raspberry pi must be accompanied by a power system to adjust the voltage and current levels of the board to those required by the process actuators [27].

5. Conclusions and discussion

There are several technologies in the market for WTP purposes. The electrocoagulation, cavitation, and ozone used separately for industrial purposes and municipal wastewater provides different removal efficiencies. This proposed chapter analyzes the benefits of using ozone for disinfection, deodoration, and adequate treatment of tap water, reuse, and recycling of wastewater. Preliminary studies developed by TRIO3 and Reingeniería en Saneamiento Ltd. demonstrate positive results using these technologies combined. The control of process variables in WWTP mentioned above involves novelty advances in ozone technology. Effective procedures discussed for the optimization of processes require more collaborative research in the usage of ozone.

Acknowledgements

Thanks to TECNM Campus Zacatecas Norte, TRIO3® Food Technologies and Reingeniería en Saneamiento Ambiental Ltd.

Nomenclature

PAH Polycyclic aromatic hydrocarbons
PCB Polychlorinated biphenyls compounds
PHC Petroleum hydrocarbon contamination

A. Appendix 1: A comparison of cavitation against other traditional techniques

Characteristics	Cavitation	Chemical	Biological	Reverse osmosis
Average cost per m^3 of treated water (Mex. Pesos)	7	12	15.0–30.0	30.0
Consumption of electrical energy per m^3 of treated water	4.5 kwh × m^3	4–6 kwh × m^3	12–15 kwh × m^3	3–12 kwh × m^3
Space required per m^3 of treated water		1	4	1
Process time per m^3 of treated water	22 min	1 h	23 h	30 min
Recycling and reuse of treated water	Partially	No	No	No
Possibility of expansion after entering into operation	Yes	No	No	No

Characteristics	Cavitation	Chemical	Biological	Reverse osmosis
Different water qualities using the same influent	Adaptable	No	No	No
Can treat residual wastewater?	Yes	Yes	Yes	No
Can obtain potable water?	Yes	No	No	Yes
A pretreatment before the process is required.	No	Yes	Yes	Yes
A residence time and stabilization stage are mandatory.	No	Yes	No	No
Modular expansion of the plant	Yes	No	No	No

B. Appendix 2: Contaminants concentration before and after use of electroflocculation technology including percentage of removal action (efficiency)

contaminant	Before (mg/L)	After (mg/L)	Total Removed (%)
Aldrin (pesticide)	0.063	0.001	98.4
Aluminum	224	0.69	99.69
Ammonia	49	19.4	60.41
Arsenic	0.076	<0.0022	97.12
Barium	0.0145	<0.0010	93.1
Benzene	90.1	0.359	99.6
BOD	1050	14	98.67
Boron	4.86	1.41	70.98
Cadmium	0.01252	<0.0040	96.81
Calcium	1321.00	21.4	98.4
Chlorieviphos (pesticide)	5.87	0.03	99.5
Chromium	1.39	<0.1000	99.92
Cobalt	0.1238	0.0214	82.71
Copper	0.7984	<0.0020	99.75
Cyanide (free)	723	<0.0200	99.99
Cypermethrin (pesticide)	1.3	0.07	94.6
DDT (pesticide)	0.261	0.002	99.2
Diazinon (pesticide)	34	0.21	99.4
Ethyl Berzene	428	0.372	99.91
Fluoride	1.1	0.415	62.27
Gold	5.72	1.38	75.87
Iron	68.34	0.1939	99.72
Lead	0.59	0.0032	99.46
Lindane (pesticide)	0.143	0.001	99.3
Magnesium	13.15	0.0444	99.66

contaminant	Before (mg/L)	After (mg/L)	Total Removed (%)
Magnanese	1.061	0.0184	98.27
Mercury	0.72	< 0.0031	98.45
Molybdenum	0.35	0.029	91.71
MP-Xylene	41.6	0.057	99.86
MTBE	21.58	0.0462	99.79
Nickel	183	0.07	99.96
Nitrate	11.7	2.6	77.78
Nitrite	21	12	42.86
Nitrogen TKN	1118,88	59.08	94.72
NTU	35.38	0.32	99.1

Author details

Carlos Martín Enríquez Castro[1]*, Manuel Pérez Nafarrate[2], Anuar Manuel Badillo Olvera[3] and César Guzmán Martínez[4]

1 Food Engineering and Technology Program, TECNM Campus Zacatecas Norte, Río Grande, Zacatecas, México

2 TRIO3 Innovation Technologies and Reingeniería en Saneamiento Ambiental Ltd. Guadalajara, Jalisco, México

3 Electromechanical Engineering Program, TECNM Campus Zacatecas Norte, Río Grande, Zacatecas, México

4 Appalachian State University, Boone, NC, USA

*Address all correspondence to: carlos.ec@zacatecasnte.tecnm.mx

References

[1] Enríquez-Castro CM, Pérez-Nafarrate M, Gerardo Rodríguez JE. Innovation in food products using ozone technology: Impact on quality assurance. In: Innovation in the Food Sector through the Valorization of Food and Agro-Food by-Products. London, UK, London, UK: Intech Open; 2021

[2] Oner ME, Demirci A. Ozone for food decontamination: Theory and applications. Handbook of hygiene control in the food industry. 2016;491-501

[3] Kim J-G, Ahmed EY, Sandhya D. Application of ozone for enhancing the microbiological safety and quality of foods: A review. Journal of Food Protection. 1999;**62**(9):1071-1087

[4] Krstović S, Krulj J, Jaksic S, Bocarov-Stancic A, Jajic I, et al. Ozone as decontaminating agent for ground corn containing deoxynivalenol, zearalenone, and ochratoxin a. Cereal Chemistry. 2021;**98**(1):135-143

[5] Schirrmeister JF, Liebenow AL, Petz K, Wittmer A, Serr A, Hellwig E, et al. New bacterial compositions in root-filled teeth with periradicular lesions. Journal of Endodontics. 2009;**35**(2): 169-174

[6] Asfahl KL, Savin MC. Destruction of *Escherichia coli* and broad-host-range plasmid DNA in treated wastewater by dissolved ozone disinfection under laboratory and field conditions. Advances in Microbiology. 2012;**2**:1-7

[7] Wu Z, Shen H, Ondruschka B, Zhang Y, Wang W, Bremner DH. Removal of blue-green algae using the hybrid method of hydrodynamic cavitation and ozonation. Journal of Hazardous Materials. 2012;**235**:152-158

[8] Jain K, Patel AS, Pardhi VP, Flora SJS. Nanotechnology in wastewater management: A new paradigm towards wastewater treatment. Molecules. 2021; **26**(6):1797

[9] Nisar MA, Ross KE, Brown MH, Bentham R, Whiley H. *Legionella pneumophila* and protozoan hosts: Implications for the control of hospital and potable water systems. Pathogens. 2020;**9**(4):286

[10] Foster J, Sommers BS, Gucker SN, Blankson IM, Adamovski G. Perspectives on the interaction of plasmas with liquid water for water purification. IEEE Transactions on Plasma Science. 2012; **40**(5):1311-1323

[11] Asaithambi P, Govindararajan R, Yesuf MB, Selvakumar P, Alemayehu E, et al. Enhanced treatment of landfill leachate wastewater using sono (US)-ozone (O3)–electrocoagulation (EC) process: Role of process parameters on color, COD and electrical energy consumption. Process Safety and Environmental Protection. 2020;**142**: 212-218

[12] Östman M, Bjorlenius B, Fick J, Tysklind M. Effect of full-scale ozonation and pilot-scale granular activated carbon on the removal of biocides, antimycotics and antibiotics in a sewage treatment plant. Science of the Total Environment. 2019;**649**: 1117-1123

[13] Li W, Li C, Zhu N, Yuan H, Shen Y. The extent of sludge solubilization allows to estimate the efficacy of ozonation for removal of polycyclic aromatic hydrocarbons (PAHs) in municipal sewage sludge. Journal of Hazardous Materials. 2021;**413**:125404

[14] Wang J, Zhang X, Li G. Effects of ozonation on soil organic matter of contaminated soil containing residual oil. Journal of Soils and Sediments. 2012; **12**(2):117-127

[15] Ried A, Mielcke J, Wieland A. The potential use of ozone in municipal wastewater. Ozone: Science & Engineering. 2009;**31**(6):415-421

[16] Gogate PR, Mededovic-Thagard S, McGuire D, Chapas G, Blackmon J, Cathey R. Hybrid reactor based on combined cavitation and ozonation: From concept to practical reality. Ultrasonics Sonochemistry. 2014;**21**(2): 590-598

[17] Bilińska L, Blus K, Gmurek M, Ledakowicz S. Coupling of electrocoagulation and ozone treatment for textile wastewater reuse. Chemical Engineering Journal. 2019;**358**:992-1001

[18] Barrera-Díaz CE, Balderas-Hernández P, Bilyeu B. Electrocoagulation: Fundamentals and prospectives. In: Electrochemical water and wastewater treatment. 2018; 61-76

[19] Čehovin M et al. Hydrodynamic cavitation in combination with the ozone, hydrogen peroxide and the UV-based advanced oxidation processes for the removal of natural organic matter from drinking water. Ultrasonics Sonochemistry. 2017;**37**:394-404

[20] Bruggeman P, Schram DC. On OH production in water containing atmospheric pressure plasmas. Plasma Sources Science and Technology. 2010; **19**:045025

[21] Gardoni D, Vailati A, Canziani R. Decay of ozone in water: A review. Ozone: Science & Engineering. 2012; **34**(4):233-242

[22] Wang R, Jiaqi L, Xianbin GJ. Design and simulation of an ozone catalytic oxidation system based on programmable logic controller. Journal Européen des Systèmes Automatises. 2020;**53**:517-524

[23] Hong S-W, Choi Y, Kim SJ, Kwon G. Pilot-testing an alternative on-site wastewater treatment system for small communities and its automatic control. Water Science and Technology 2005;**51** (10):101-108

[24] Manesis SA, Sapidis DJ, King RE. Intelligent control of wastewater treatment plants. Artificial Intelligence in Engineering. 1998;**12**(3):275-281

[25] Humoreanu B, Nascu I. Wastewater treatment plant SCADA application. In: Proceedings of 2012 IEEE International Conference on Automation, Quality and Testing, Robotics. 2012:575-580

[26] Hamidi EAZ, Gustiana T, Effendi MR, Hambali PAM. Design and implementation supervisory control and data acquisition (SCADA) of flocculation process of water treatment plant (WTP) using raspberry pi. In: Proceeding of 2019 IEEE 5th International Conference on Wireless and Telematics (ICWT). 2019; 1-5

[27] Upadhyay D, Sampalli S. SCADA (supervisory control and data acquisition) systems: Vulnerability assessment and security recommendations. Computers & Security. 2020;**89**:101666