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Risk Management in reclaimed water reuse

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Abstract

Water is a natural resource essential for life and whose correct management is vital. Due to the lack of water resources, the reuse of urban wastewater has been increasing in recent years, to reduce water stress and avoid pollution caused by discharges. Water must be treated to meet the desirable quality, before being applied for different uses, as required in the current legislation. With the current treatment, the Gaia Litoral wastewater treatment plant is capable of producing water that meets the standard parameters for class A water, except for *E. coli* concentration. In this work, an ozonation treatment was studied as a disinfection step (removal of microorganisms), to improve the effluent quality of this plant. A risk assessment analysis was also conducted to understand the viability of the water reuse project.

Initially, three different hydraulic residence times (HRT) (2.0, 4.0 and 5.5 min) were tested in the ozonation treatment. The collected samples presented similar faecal coliforms and *E. coli* concentration for the three different HRTs, so the lowest HRT was chosen to further test the ozonation system at six different transferred ozone dosages (TOD) (7.1, 11.4, 16.4, 17.9, 19.4 and 21.8 mg/L). It was verified that the disinfection increases with the TOD, with a significant increase in the disinfection was found for a TOD of 17.9 mg/L. At TODs of 17.9 mg/L or higher, all the samples presented *E. coli* concentrations below 100 CFU/100 mL and some below 10 CFU/100 mL. Although 75% of the samples presented *E. coli* concentrations below 10 CFU/100 mL for a TOD of 21.8 mg/L, the required 90% were not achieved, so it was not possible to produce class A water. The suggested TOD to be applied at the plant is 17.9 mg/L, which is sufficient to produce class B water (BOD_5 below 25 mg/L, total suspended solids (TSS) below 35 mg/L and *E. coli* below 100 CFU/100 mL).

For the risk assessment analysis it was considered the guidelines published by the *Agência Portuguesa do Ambiente* (APA), which follows a semi-quantitative model proposed by Saaty (1980). The irrigation of green spaces of a park was identified as the main possible application for the water reuse. Regarding the public health risk, it was obtained a 1.77 risk for adult users, 2.17 for maintenance workers, 2.37 for child users, and a global risk of 2.10 which, according to APA, is considered negligible. As for the environmental risk, the highest value was 3.89, which was determined for the concentration of P and N and represents an acceptable risk.

Overall, it was possible to treat the wastewater from the Gaia Litoral wastewater treatment plant with an ozonation step to produce reclaimed water that complies with the legislation for class B water. The risk assessment analysis developed for the reuse of the treated water for park irrigation found negligible risk for public health and an acceptable risk for the environment, which proves the viability of the project.

Keywords: Ozone treatment, water reuse, risk assessment

Resumo

A água é um recurso natural essencial à vida e cuja gestão correta é essencial. Devido à escassez de recursos hídricos, a reutilização de águas residuais urbanas tem aumentado, para reduzir o stress hídrico e evitar a poluição causada por descargas. A água deve ser tratada para atingir a qualidade adequada, antes de ser aplicada para diversos usos, conforme legalmente exigido. Com o tratamento atual, a estação de tratamentos de água residual de Gaia Litoral é produz água que cumpre com parâmetros padrão exigidos para água de classe A, exceto no que diz respeito à concentração de *E. coli*. Neste trabalho, estudou-se um tratamento de ozonização para desinfeção (remoção de microrganismos), para melhorar a qualidade do efluente da estação. Também foi realizada uma análise de avaliação de risco para entender a viabilidade do projeto de reutilização da água.

Inicialmente, testaram-se três diferentes tempos de residência hidráulica (HRT) (2.0, 4.0 e 5.5 min), no tratamento de ozonização. As amostras analisadas apresentaram concentrações de coliformes fecais e *E. coli* semelhantes para os diferentes HRT. Assim, escolheu-se um HRT de 2 min para testar o sistema de ozonização com seis diferentes doses de ozono transferido (TOD) (7.1, 11.4, 16.4, 17.9, 19.4 e 21.8 mg/L). Verificou-se que a desinfeção aumenta com a TOD, tendo sido encontrado um aumento significativo na desinfeção para uma TOD de 17.9 mg/L. Em TODs de 17.9 mg/L ou superiores, todas as amostras apresentaram concentrações de *E. coli* inferiores a 100 UFC/100 mL e algumas inferiores a 10 UFC/100 mL. Embora 75% das amostras apresentasse concentração de *E. coli* inferiores a 10 UFC/100 mL para uma TOD de 21.8 mg/L, não foram atingidos os 90% requeridos, impedindo a classificação da água como classe A. Assim, a TOD a aplicar na estação deve ser 17.9 mg/L, suficiente para produzir água classe B (BOD_5 inferior a 25 mg/L, TSS inferior a 35 mg/L e *E. coli* inferior a 100 UFC/100 mL).

Para a análise de avaliação de risco, foram consideradas as orientações publicadas pela Agência Portuguesa do Ambiente (APA), que segue o modelo semi-quantitativo proposto por Saaty (1980). A irrigação de espaços verdes de um parque foi identificada como a principal aplicação possível para a reutilização da água tratada. Para o risco da saúde pública, obteve-se um risco de 1.77 para os utilizadores maiores de idade e 2.37 para menores, 2.17 para trabalhadores de manutenção e um risco global de 2.10, considerado desprezável pela APA. Quanto ao risco ambiental, atingiu-se um valor global máximo de 3.89, considerado aceitável.

Globalmente, foi possível tratar as águas residuais da estação com uma etapa de ozonização, para produzir águas para reutilização que cumprem a legislação para águas de classe B. A análise de avaliação de risco da reutilização da água tratada para irrigação do parque encontrou risco desprezável para a saúde pública e um risco aceitável para o meio ambiente, o que comprova a viabilidade do projeto.

Palavras-chave: Tratamento com ozono, reutilização de água, avaliação de risco

Declaração

Declara, sob compromisso de honra, que este trabalho é original e que todas as contribuições não originais foram devidamente referenciadas com identificação da fonte.

Francisco Ribeiro Rocha, 4 de julho de 2022

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Abbreviations

TOD	Transferred ozone dose	mg/L
Q_{gas}	Gas flow rate	m^3/h
Q_{liq}	Water flow rate	m^3/h
$[O_3]_{gas\ in}$	Feed gas ozone concentration	mg/L
$[O_3]_{gas\ out}$	Outlet gas ozone concentration	mg/L
V_r	Receptor Vulnerability	
$f_{i\ route}$	Exposure Route	
$f_{i\ scenario}$	Exposure Scenario	
$f_{exposure}$	Normalization Factor	
f_{max}	Maximum Importance Factor	
d_i	Damage	
D	Total Damage	
n_i	Number of Equivalent Barriers	
$R_{receptor}$	Receptor Risk	
H	Hazard Level	
R_G	Global Public Health Risk	
$n_{receptor}$	Number of Receptors	
V_{wr}	Water Resources Vulnerability	
V_{sup}	Superficial Water Vulnerability	
V_{under}	Underground Water Vulnerability	
V_G	Global Vulnerability	
$f_{i\ barrier}$	Barrier Importance Factor	
R_{WR}	Global Environmental Risk	

APA	Agência Portuguesa do Ambiente
CFU	Colony-Forming Unit
E. coli	*Escherichia coli*
HRT	Hydraulic Retention Time
PPE	Personal Protective Equipment
TOC	Transferred Ozone Dose
WWTP	Wastewater Treatment Plant

1 Background

1.1 Project Presentation

Water is a natural resource essential for life with unreplaceable environmental, social, and economic value. Due to population growth, unsustainable management and climate changes, water is becoming a scarce resource. By 2025, up to 3.5 billion people could experience water scarcity and the demand is projected to grow up to 30% by 2050 (WRI, 2022). By 2040, it is expected that Portugal faces similar risk, occupying the 44th place in a ranking of the most water-stressed countries, according to a study made by the World Resources Institute (WRI, 2015). For these reasons, it is important to manage water resources correctly, assuring their efficient use and treatment. Due to the lack of water resources, reuse of urban wastewater has been increasing in recent years, whose safe implementation depends on the treatment applied (Gómez et al., 2006).

Wastewater treatment consists of a combination of physical, chemical, or biological processes to improve the quality of wastewater and return the obtained effluent to the environment safely or for reuse (Nizamuddin et al., 2019). Water must be treated to meet the desirable quality based on its potential use, such as discharges to the environment (ocean waters or rivers), irrigation, industrial reuse, etc. Wastewater management allows a sustainable development in the use of water resources, i.e., meeting current needs without compromising its future (Englande et al., 2015). It has a fundamental role in ensuring public health and environmental quality. In Europe, in 2017, most of the population was connected to urban wastewater treatment facilities, with an increasing progress since the adoption of the Urban Waste Water Treatment Directive in 1991 (EEA, 2021).

Water reuse, defined as the process of using treated wastewater for beneficial purposes (Sun et al., 2011), is becoming an increasingly important alternative to offer opportunities to reduce water stress and avoid pollution caused by discharges. It has been applied in irrigation, industrial processes, groundwater recharge, street washing, among others. The development of new wastewater treatments, has allowed to improve the quality of the final effluents, thus opening more options for their potential reuse. However, the environmental and public health risks associated with each application must be taken into consideration due to pathogenic microorganisms, disinfection by-products and compounds of emerging concern that can resist conventional treatment (Rebelo et al., 2020). Costs with infrastructures, facilities and treatment reliability are important variables to understand economic and financial viability. The return of the water from the wastewater treatment facility to areas where it can present benefit is often considered a key limiting factor to the implementation of water reuse systems

(Leverenz & Asano, 2011). In 2020, the European Parliament and the Council of the European Union created a legislation that imposes limits to parameters such as biological oxygen demand (BOD_5), total suspended solids (TSS), turbidity and *E. coli*, that need to be assessed and controlled (EU, 2020). In Portugal, there is also a growing awareness of the importance of water reuse after the publication of Decree-Law n.º 119/2019 and the inclusion of the topic in the national strategies that allows a variety of potential applications. It can be used as an important sustainable management tool for the conservation of water resources in the country. To further advance, it is essential to understand the impact each application can have on the environment and public health.

At the moment, the Gaia Litoral wastewater treatment plant (WWTP) produces treated water that does not comply with the legislated parameters for water reuse, particularly *E. coli*, after the current tertiary treatment which includes coagulation, sand filtration and UV radiation. In this work, an alternative tertiary treatment – ozonation – was studied with the objective of obtaining a treated residual water that meets the legislation established for its reuse. Another goal for this project was to study different applications for water reuse and develop a risk assessment and management strategy accordingly.

1.2 Company Presentation

This work was developed in partnership with SIMDOURO, Saneamento do Grande Porto, S.A., with headquarters in Gaia Litoral WWTP (Vila Nova de Gaia, Portugal). Created in 2009 with exclusively public capital, is responsible for the construction, management and concession of the multi-municipal sanitation of the Greater Porto, in exclusivity for a period of 50 years (SIMDOURO, 2017). SIMDOURO's goal is to collect, treat and reject municipal wastewater with efficiency and reliability respecting social and environmental sustainability. It works with the municipalities of Arouca, Baião, Castelo de Paiva, Cinfães, Paredes, Vila Nova de Gaia and Penafiel (Sousa River basin), which corresponds to an area of 1300 km^2 and 519,000 inhabitants. Águas de Portugal, SGPS, S.A. owns 58.52% of the capital and the remainder belongs to the above-mentioned municipalities (SIMDOURO, 2017). Águas de Portugal is a public group that has several companies throughout Portugal with its main activities in water supply and sanitation (AdP, 2015b). It plays an important role in resource management, public policies, and national objectives within the environmental domain. Its commitment is to adapt and respond to climate change, decarbonization, digital transformation and circular economy allowing a more efficient use of resources while improving the quality of the water and its service to the population (AdP, 2015a). In 2020, the companies of the group were responsible for a total of 1004 WWTP's with a total of 532.4 million m^3 of wastewater treated and returned to nature.

2 Introduction

2.1 Wastewater Reuse Guidelines

The following information is based on the Guide for Non-potable Water Reuse developed by the *Agência Portuguesa do Ambiente* (APA)(APA, 2019). It provides guidelines for licensing of production and use of water for reuse and guidelines for risk assessment and management in Portugal. This guide is considered a crucial tool for the development of water reuse projects and compliance with the current legislation in Portugal.

Each application for water reuse implies specific water quality standards, that need to be met accordingly by the treatment level used. The water quality must comply with the regulations, however the use of highly treated water for general applications will increase its cost without providing any advantage, which can discourage reuse (Capodaglio, 2021). For these reasons, it is important to consider a fit-for-purpose approach that can provide the adequate water quality for each application.

Systems for reuse can be defined as centralized or decentralized. Centralized systems use water from urban WWTPs, in which the delivery point must be defined according to the water quality required. They can have a simple delivery point, where the water is produced to a certain quality to be used by one or multiple users, or multiple delivery points with different water quality. The systems with multiple delivery points can work in parallel or in series or in a combination of both, depending on the goal of each project. Centralized systems have the responsibility of delivering water with the necessary quality upstream of the delivery point, from which the end user is responsible for maintaining its quality until the point of application. Decentralized systems are managed by a private entity that reuses the produced water and cannot provide it to other users. The present work was developed at a WWTP with the goal of producing water for reuse for different users, so the centralized system was considered. The market for reuse in these systems may be limited to the surroundings of the plant, since the reuse for remote locations requires a costly investment in infrastructures for distribution systems (Asano, 2007).

The development of projects that allow water reuse must go through several stages. Initially, contacts between the centralized system and potential users must be made to understand the demand for water reuse and the necessary quality for each application. Contacts that have a low predicted demand that do not justify the implementation of a production system for water reuse or defined delivery points too far from the central plant can be disregarded. If it is established that the conditions to produce water are in accordance with potential users and it justifies the necessary investment, there is the need for a risk assessment evaluation from the production of water until its end use. Risk assessment is a scientific method that expresses the uncertainty over the prediction of future events, which is based on identifying associated hazards of a process or situation and estimating the risks (Lohani et al., 1997). The risks associated with wastewater reuse are related to its chemical and microbiological characterization and can have an impact on public health and the environment (Shakir et al., 2017). In this work, a risk assessment analysis was conducted for both.

For potable water reuse, the risk assessment analysis should follow the Quantitative Microbial Risk Assessment (QMRA) proposed by the World Health Organization (WHO, 2006). This methodology requires extensive and reliable data. For non-potable water reuse, the lack of data for exposure routes and epidemiologic studies presents a challenge for the application of quantitative methods. For such cases, the use of qualitative or semi-quantitative methods, based on the application of matrices and importance factors scales, can be a more appropriate approach (Rebelo et al., 2014). This work was focused on non-potable water reuse so it will follow a semi-quantitative model proposed by Saaty (1980), based on importance factor scales. The importance factors will be attributed to different exposure routes and scenarios based on the APA guidelines and the available literature. The risk assessment strategies include identification of hazards, receptors and exposure routes, application of barriers and risk characterization, which are further discussed in section 4.3 Risk Assessment.

After verification of the viability of the project, the licenses for the production and utilization of water for reuse must be requested to the APA. The analysis conducted for the risk assessment is one of the fundamental factors to obtain the licence. The centralized management system must request a license for production, which includes the use of the water for internal or external purposes. Then, a license for water reuse must be requested by the entity responsible for its end use to the local *Administração Regional de Saúde* (ARS) and, in case of forest or agricultural irrigation, to the *Direção Regional de Agricultura e Pescas* (DRAP).

The risk assessment analysis also includes the selection of quality standards at the delivery and application points. Monitoring plans need to be prepared to assure the compliance with the terms described in the license that was previously obtained for the production and use. These include control over the water parameters, such as *E. coli* concentration, TSS or BOD_5, and operational control over the equipment (*e.g.,* flow control, pressure drop in filters) and the barriers used. The latter are physical or chemical barriers that can be applied in different stages of the system, such as treatment, distribution, storage, or application. The use of disinfection, physical barriers, or access control to areas where the water was used are examples of barriers typically used. Measures to deal with abnormal situations should also be predicted and described preventively (Rebelo et al., 2020).

SIMDOURO had already established contacts with companies that would be interested in reusing the treated water nearby the Gaia Litoral plant, most of them related to irrigation of gardens, crops, or golf courses, and pavement and vehicles washing (*e.g.,* vehicle cleaning at gas stations). APA guidelines divide water for reuse into different quality classes (from A to E) allowing different uses. The classes are established according to different water quality parameters as explained in Table 1.

Table 1 - Quality classification of water for reuse (APA, 2019).

Quality Class	**BOD_5** (mg/L O_2)	**TSS** (mg/L)	**Turbidity** (NTU)	***E. coli*** (CFU/100 mL)	**Intestinal Parasites Eggs**[a] (N/L)	**NH_4^+** [b] (mg/mL)	**N** [b] (mg/mL)	**P** [b] (mg/mL)
A	≤ 10	≤ 10	≤ 5	≤ 10		10	15	5
B	≤ 25	≤ 35		≤ 100				
C	≤ 25	≤ 35		≤ 1000	≤ 1			
D	≤ 25	≤ 35		≤ 10000	≤ 1			
E[c]	≤ 40	≤ 60		≤ 10000				

[a] Applicable for agricultural irrigation of crops for animal feeding.
[b] Optional parameter. May only be applicable for minimization of biofilms formation and irrigation system obstruction.
[c] Applicable only for decentralized systems.

The uses allowed by class for different irrigation purposes are described in Table 2. In the case of pavement or vehicle washing, the APA guidelines state that, for high pressure systems, the required water quality should be considered as class A (APA, 2019).

Table 2 - Possible uses for the different water quality classes (APA, 2019).

Quality Class	Possible Uses
A	Irrigation without restricted access: food crops consumed raw, where the edible part is in direct contact with water; public and private gardens.
B	Irrigation with restricted access: food crops consumed raw, that grow above surface, where the edible part is not in direct contact with water; agricultural crops for processing and for animal feeding (milk production or meat), except swine; gardens with restricted access, including leisure and sports areas (*e.g.*, golf courses).
C	Irrigation with restricted access: food crops consumed raw, that grow above surface, where the edible part is not in direct contact with water; agricultural crops for processing and for animal feeding (milk production or meat), except swine.
D	Irrigation with restricted access: Industrial, energy and seeded crops.
E	Irrigation with restricted access: seeded crops; areas of restricted use (such as hedges or terrace fields).

The APA guidelines also establish the minimum number of barriers that need to be applied for a certain water quality class to be applied for different irrigation uses. Table 3 presents this information for a lower quality water to be used for stricter purposes.

Table 3 - Minimum number of barriers to be applied for each quality class for different uses (APA, 2019).

Quality Class	Irrigation without restricted access	Irrigation with restricted access	Food crops consumed raw	Crops for processing and for animal feeding, except swine	Orchards	Seeded crops	Seeded crops/Other private areas with restrict use
A	0	0	0	0	0	0	0
B	1	0	1	0	0	0	0
C	Forbidden	1	3	2	1	0	0
D	Forbidden	Forbidden	Forbidden	Forbidden	3	0	0
E	Forbidden	Forbidden	Forbidden	Forbidden	2	1	0

The information on Table 3 is not enough, by itself, to allow the reuse of the treated water. It can be used as guide, but it does not dismiss the need for the all the risk assessment process and analysis (APA, 2019). At the beginning of the work, Gaia Litoral WWTP was only capable of producing treated water of quality class D or lower, which did not meet the minimum quality required for irrigation. The treatments performed in this WWTP are described in the subsequent section, as well as a potential additional treatment with ozone, intended to be implemented with the objective of achieving a water quality class of B or higher.

2.2 Gaia Litoral Wastewater Treatment Plant

Initially, the affluent suffers a preliminary treatment, in which it is subjected to a screening process. This process is used to remove coarse materials that are present in urban wastewater and can cause damage or disturb the subsequent equipment and processes. It consists of two mechanically cleaned bar screens, that work in parallel, with 10 mm width between bars. There is also a reserve manual clean bar screen with 20 mm width between bars in case there is any problem with the ones in work. The solids are stored in a container and collected by external companies that are responsible for their treatment. Then, the water follows to the primary treatment (Sedipac™ 3D), a process that is responsible for the removal of sand and other small particles, grease, and suspended matter (Águas de Gaia, 2003). There are 2 devices working in parallel, each with four grit chambers. In these chambers, the flux is forced to the bottom, which enhances the removal of sand and other small particles. In the next section of the equipment, air bubbles are generated at the bottom to remove hydrophobic particles through flotation. Here, there is an up flow of the effluent that facilitates the removal of hydrophobic particles that adhere to the air bubbles (Águas de Gaia, 2003). The use of different compartments for grit removal and flotation allows the use of flows with different directions, which increases the yield of each step (Águas de Gaia, 2003). For the removal of suspended materials, a settling process is used with a lamellar decanter. It allows higher velocities than conventional decanters due to the high surface area, which results in a smaller floor area occupied by the equipment (Águas de Gaia, 2003). The removed materials, such as sand and grease, are stored to be collected by external companies, while the primary sludge resulting from the settling process heads to the thickener.

The secondary treatment is composed of aerobic reactors with activated sludge and secondary settling. In the aerobic reactors, microorganisms form biological flocs under aerobic conditions provided by bottom diffusers. These microorganisms are responsible for the oxidation of carbonaceous organic matter into simple end-products and the removal of nitrogen and phosphorous (Metcalf & Eddy, 2003). The WWTP uses four reactors working in parallel, which allows more flexibility. Four rectangular clarifiers are responsible for the secondary settling, which results in the gravitational separation of the sludge from the water. Currently, most of the water treated is discharged to the Atlantic Ocean, while a small fraction goes through tertiary treatment to be reused internally for cleaning and irrigation. The sludge removed from the secondary settlers can be recirculated to the biological reactors or removed to the flotation tank. The primary and secondary sludge are blended and forwarded to an anaerobic digestor where biogas is produced. This renewable fuel is used in the cogeneration of heat and electricity for internal consumption. The digested sludge suffers dehydration to reduce its volume and is stored to be collected by an external company. The schematic diagram of the wastewater treatment process in Gaia Litoral WWTP is found in Figure 1 (Águas de Gaia, 2003).

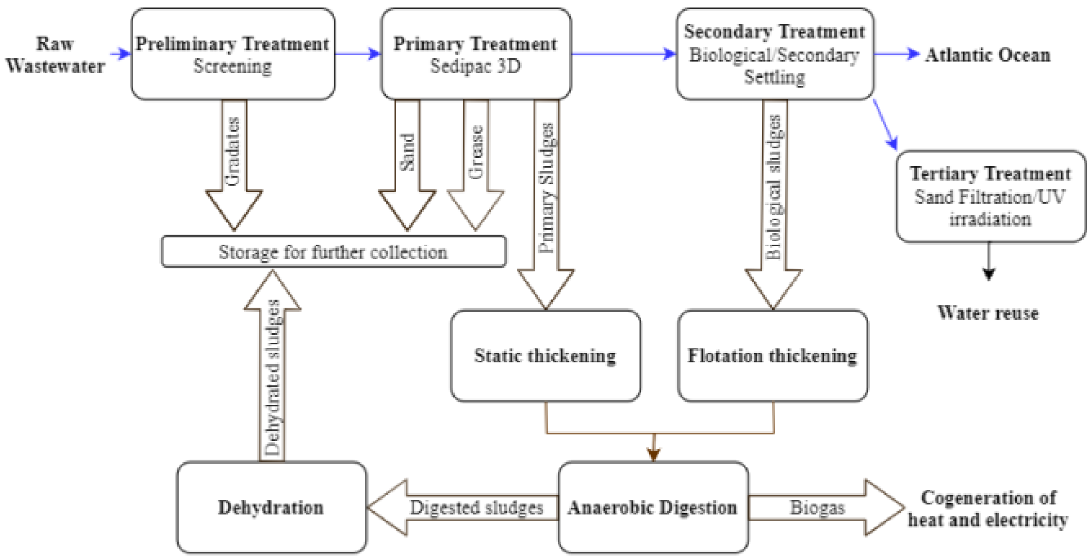

Figure 1 - Schematic diagram of the wastewater treatment process in Gaia Litoral WWTP (Venâncio, 2021).

The tertiary treatment is necessary to assure water quality levels that allow its internal reuse. It includes coagulation, filtration, and UV disinfection. A sand filter is used to reduce the total suspended solids content and turbidity, improving the effluent's transmittance when compared with the non-filtered one (from 50 to 60%) (Águas de Gaia, 2003). This improves the efficiency of the UV treatment, reducing the number of UV modules needed and, consequently, its cost. There are two filters working in series with a flow rate of 100 m^3/h. Between them there is the injection of a coagulant (aluminium sulphate), which allows the removal of suspended particles, organic matter and phosphorus (Li et al., 2017). The UV disinfection removes microorganisms present in the effluent destroying its DNA strands at a wavelength of 253 nm. The system is composed by 5 modules, with 8 lamps each, installed horizontally in the effluent channel, flowing to a cistern where it is stored for reuse. The current system does not provide sufficient treatment for the removal of *E. coli* for water reuse purposes. For that reason, other tertiary treatments were considered for the disinfection of the wastewater from the secondary treatment.

2.3 Tertiary Treatment

In wastewater treatment it is important to remove or inactivate pathogens to protect public health. The treatment should guarantee that the water treated does not serve as vector for the transmission of diseases in the community, assuring that the treated water is microbiologically safe (Jacangelo & Trussell, 2002). This step is key to achieve water that is appropriate for its intended use and safe for both public health and the environment (Collivignarelli et al., 2017). Well established technologies include ultraviolet (UV) radiation, chlorination and ozonation (Gómez et al., 2006; Lazarova et al., 1999). More recently, studies for advanced oxidation processes (AOPs) have been developed. These processes may include the combination of oxidizing agents (H_2O_2, O_3), UV radiation and catalysis (*e.g.*, titanium dioxide, Fe^{2+}, etc) (Collivignarelli et al., 2017; Poyatos et al., 2010).

2.3.1 UV radiation

UV light is part of the electromagnetic spectrum between the 100 and 400 nm of wavelength. Water can be disinfected due to exposure to UV radiation with optimal disinfection at about 254 nm (Moran, 2018). The effectiveness of the treatment is proportional to the product of light intensity and time of exposure, commonly referred as UV dose, typically expressed in W s/cm^2 or J/cm^2 (Rajkhowa, 2020). At a wavelength of 254 nm, UV radiation penetrates the outer cell membranes and damages ribonucleic acids and deoxyribonucleic acids, which causes the inactivation of the microorganisms (Srikanth, 1995). The absorption of UV radiation forms new bonds between adjacent nucleotides, creating dimers, particularly thymine dimers, that prevent replication and result in cell death (Das, 2001). This method is more effective after the water is treated by coagulation and filtration, as the presence of particles prevents microorganisms from being fully exposed to UV rays (Hariganesh et al., 2020). These systems have proven to be effective in the inactivation of various species of bacteria and viruses, such as *E. coli* and *Hepatitis A virus* (Moran, 2018; Rajkhowa, 2020). Some advantages of the treatment include no by-products formation and short contact time, though it may demand high energy, which results in high cost (Collivignarelli et al., 2017). This is one of the steps of the tertiary treatment currently in use in Gaia Litoral WWTP. However, it is not producing sufficient results in the inactivation of *E. coli* and other faecal coliforms, and there is no compliance with the guidelines established by the APA that allow for water reuse. For these reason, other disinfection methods will be considered.

2.3.2 Chlorination

Chlorination is the most widely used disinfection method for the inactivation of pathogenic microorganisms in water and wastewater (Gómez et al., 2006). It can be achieved with liquefied chlorine gas, sodium hypochlorite solution or calcium hypochlorite granules, and on-site chlorine generators (Hariganesh et al., 2020). It has a powerful bactericidal action with complex mechanisms. The modification of the chemical structures of enzymes responsible for mechanisms of nutrition of bacteria is considered the main action of chlorine (Collivignarelli et al., 2017). Chlorine dioxide, due to high oxidative power, can inactivate enzymatic systems or interrupt protein synthesis (Cho et al., 2010). The effectiveness of the process depends on the effluent quality due to the presence of organic compounds, industrial wastes and ammonia concentration that can strongly affect chlorine demand (Lazarova et al., 1999). This treatment can be applied for drinking water and wastewater, and is considered a consolidated, easy to handle and economical technology that provides efficient disinfection (Collivignarelli et al., 2017). However, there is a major concern about the formation of by-products. In 1991, The International Agency for Research on Cancer/World Health Organization (IARC/WHO) considered chlorinated drinking water a potential human carcinogen (Villanueva, 2019). Much of the effects on biological systems of chlorinated by-products remain unknown, but there is a growing awareness to understand its impact on cancer, non-cancer, and reproductive effects based on animal and epidemiological studies (Anand et al., 2014). For safety reasons, the APA only allows the use of chlorination as residual disinfectant for the treatment of wastewater for reuse to maintain the microbiological inactivation through the storage, delivery, and application systems. The dosage should be defined based on the water chlorine demand, which is the difference between the chlorine applied and the residual chlorine. The dosage applied should minimise the residual chlorine to avoid the formation of by-products. The current system needs further disinfection than the one allowed by the APA for chlorination, so it will not be considered for this work as the main disinfection method.

2.3.3 Ozonation

Advanced oxidation processes are used for several applications in wastewater treatment, particularly with a more recent focus on the removal of emerging micropollutants (Chavoshani et al., 2020). These processes rely on the generation of reactive oxygen species, such as hydroxyl radicals (•OH), hydrogen peroxide and ozone (Chavoshani et al., 2020). The hydroxyl radicals are capable of oxidizing most organic compounds into carbon dioxide, water, and mineral acids or salts, being often considered the dominant species for pollutant degradation in these processes (Sievers, 2011).

Ozone is a strong and unstable oxidizing gas produced when oxygen molecules separate, collide and form a molecule of three oxygen atoms (Spellman, 2014). Ozone has been widely used as a disinfectant, strong oxidant, and discoloration agent for large-scale water treatment. During ozonation, several organic and inorganic pollutants can be oxidized through direct oxidation with ozone, which is a selective oxidant. Some examples include direct oxidation of Fe (II) and Mn (II), which are represented in Equation 1 and Equation 2, respectively (Escalé, 2017). Organic pollutants can also be oxidized through indirect oxidation due to the decomposition of ozone in water which may give more reactive species, such as •OH radicals, which are very fast and nonselective (Sievers, 2011). Ozone's decomposition reactions can be described as represented in Equation 3 to Equation 6 (Metcalf & Eddy, 2003). As a disinfectant, ozone presents high kill rates of fungus, bacteria, and viruses through the destruction of the organism's cell wall which exposes it to the environment and destroys the cell (Hesby, 2005).

$$2Fe^{2+} + O_3 + 5H_2O \rightarrow 2Fe(OH)_3 + O_2 + 4H^+ \quad (1)$$

$$Mn^{2+} + O_3 + H_2O \rightarrow MnO_2 + O_2 + 2H^+ \quad (2)$$

$$O_3 + H_2O \rightarrow HO_3^+ + OH^- \quad (3)$$

$$HO_3^+ + OH^- \rightarrow 2HO_2 \quad (4)$$

$$O_3 + HO_2 \rightarrow HO\cdot + 2O_2 \quad (5)$$

$$HO\cdot + H_2O \rightarrow O_2 + H_2O \quad (6)$$

A typical ozonation process layout is illustrated in Figure 2. The process requires an oxygen gas supply, an ozone generator, a gas-liquid contact tank, a degassing tank, a cooling unit for the ozone generator, a power supply, and a control unit (Sievers, 2011). The generation of ozone is expensive and its use in low concentrations requires high transfer efficiency to the wastewater to be treated (Metcalf & Eddy, 2003). Ozone is an irritating and toxic gas, so worker exposure needs to be prevented by the destruction of residual ozone from the contactor (Spellman, 2014). As ozone is an unstable gas, its generation on site is a demand, typically with electrical discharges. Equation 7 represents the collision of free, energic electrons with oxygen molecules, which allows for the generation of ozone, represented in Equation 8:

$$e^{-1} + O_2 \rightarrow 2O + e^{-1} \qquad (7)$$

$$O + O_2M \rightarrow O_3 + M \qquad (8)$$

where, $M$is any other molecule present in the gas at the same time (Alsheyab & Muñoz, 2007). Ozone's decomposition reactions are represented in Equation 9 and Equation 10 (Alsheyab & Muñoz, 2007). These reactions are promoted at higher temperatures so the use of a cooling system is necessary to maintain efficient ozone generation (Magara et al., 1995).

$$O + O_3 \rightarrow 2O_2 \qquad (9)$$

$$e^{-1} + O_3 \rightarrow O_2 + O + e^{-1} \qquad (10)$$

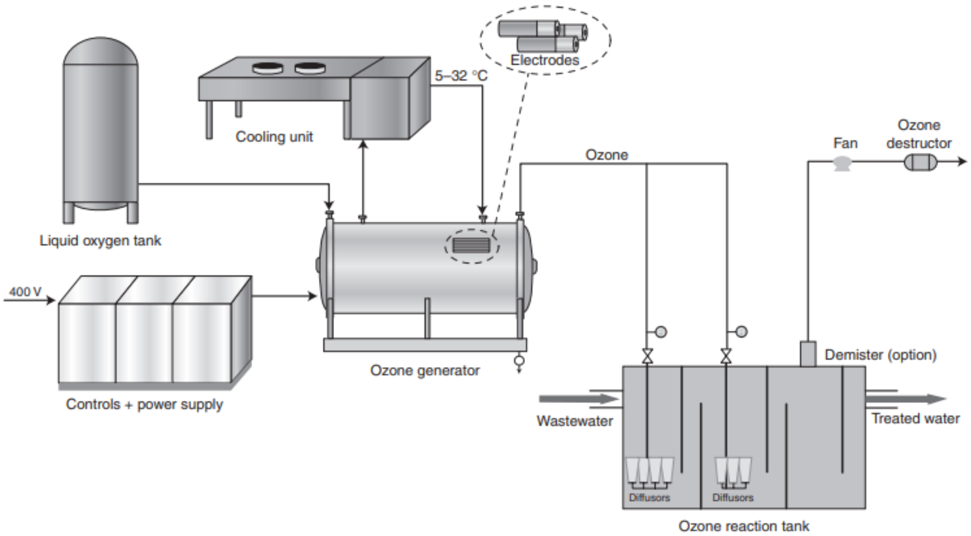

Figure 2 - Ozone system layout of ITT Wastewater GmbH Herford (Sievers, 2011).

Chlorination has been the preferred disinfection method over ozonation, namely in the United States of America due to lower capital and maintenance costs (Kinman & Rempel, 1975; Spellman, 2014). As previously mentioned, more recently there have been conducted more studies about the production of potentially hazardous by-products with the use of chlorine as the main disinfectant (Xu et al., 2002). As an alternative, ozonation requires shorter contact time than chlorination and is capable of odour and colour removal (Drinan & Spellman, 2012). Ozonation is considered a highly effective disinfectant with no significant production of by-products, although bromate needs to be monitored (von Gunten, 2003). This is a potential carcinogenic compound that can be formed from the oxidation of bromide through a combination of ozone and ˙OH radical reactions, which includes up to six oxidation states of bromine (von Gunten, 2003).

3 State of the Art

The experimental use of ozone as a disinfectant of municipal wastewater is dated back to 1892, while the first major plant to start using the treatment was in 1906 in Nice, France (Kinman & Rempel, 1975).

Several studies have been conducted over the past, in lab and pilot scale at different WWTPs to understand the effect of ozone disinfection on indicator bacteria, as represented in Table 4. The ozone dosages applied are in a wide range of values, which can be explained by the characteristics of the different effluents and treatments applied before the ozonation step and to the disinfection goals related to each study. Municipal wastewaters are a complex mixture of waters with different origins, which can also impact the efficiency of the ozone treatment (Ried et al., 2009). Gehr et al. (2003) reported that the high ozone dosages applied for a sufficient disinfection may be related to the presence of organics, as its effluent only suffered a primary treatment. The results obtained by Liberti and Notarnicola (1999) show that, for the same ozonation conditions, the ozone treatment produced higher disinfection levels for the effluent with higher treatment level. These results support the conclusion that the characteristics of the effluent can interfere with the efficiency of the ozone disinfection applied. The different studies also applied different hydraulic retention times (HRTs). Paraskeva and Graham (2005) tested different conditions and concluded that, contrary to the transferred oxygen dose (TOD), HRT was not a critical parameter. These results are supported by the data obtained by Xu et al. (2002), that tested different HRTs and TODs in different effluents from different WWTPs. They concluded that there was no significant impact of the different contact times tested, which can be attributed to the fast kinetics of the ozone reactions with the different compounds and bacteria (Xu et al., 2002). In this study, it is also possible to observe that different effluents with different treatment levels required different ozone dosages to obtain the same disinfection level (Xu et al., 2002).

In the USA, ozonation is the least used disinfection treatment, although there is a growing interest in the use of this technology due to stricter regulations and water shortages (Oneby et al., 2010). The use of ozone as a tertiary treatment was only applied in 7 different WWTPs in the USA as of 2010, in areas where water reuse is particularly significant (Oneby et al., 2010).

Table 5 represents the location of these facilities, the average dry weather flowrate and the ozone dose. It is possible to observe that the flow rate of these WWTPs varies between 1,100 m^3/h and 7,900 m^3/h, with ozone dosages comprehended between 1.3 mg/L and 27 mg/L. The wide range of the ozone dosages can be explained by the different characteristics of the different effluents, to different legislation set by the different states or to the end-use of the effluent after ozonation.

Table 4 - Studies on ozone disinfection on indicator bacteria (adapted from Paraskeva and Graham (2002)).

Reference	Type of Effluent	Ozone Dose (mg/L)	HRT (min)	Microorganism	Initial Conc. (CFU/100 mL)	Final Conc. (CFU/100 mL)
Nebel et al. (1973)	Secondary	12.8 – 16.2	5	FC	5.2×10^4 – 8.5×10^5	32 – 8×10^2
				TC	4.0×10^5 – 9.2×10^6	47 – 2.7×10^3
Liberti and Notarnicola (1999)	Secondary Clarified	15	10	TC	1.4×10^6	1.1×10^3
Liberti and Notarnicola (1999)	Secondary Filtered	15	10	TC	8.0×10^5	97
Gehr et al. (2003)	Primary	30 – 50	n/a	FC	6.0×10^5 – 3.0×10^7	1.0×10^3 – 1.0×10^4
Paraskeva and Graham (2005)	Secondary	2 – 3	n/a	EC	4.0×10^3 - 4.0×10^4	100
		2.5 – 5	n/a	TC	4.0×10^4 - 2.5×10^5	100

FC – faecal coliforms; TC – total coliforms; EC – *E. coli*; n/a – not available; HRT – hydraulic residence time.

Table 5 - Operating WWTPs in USA with ozone treatment, as of 2009 (Oneby et al., 2010).

Location	Average Dry Weather Flowrate (m^3/h)	Ozone Dose (mg/L)
Mahoning County, Ohio	1,300	4
Springfield, Missouri	4,700	3
Frankfort, Kentucky	6,300	4-8
Hagerstown, Maryland	1,900	10
El Paso, Texas	1,600	5.4
Trion, Georgia	1,300	27
Gwinnett County, Georgia	7,900	1.3

Other WWTPs present in Japan, Korea, Europe, used ozonation mainly as a disinfection step for effluent discharge (Paraskeva & Graham, 2002). It is expected that the use of ozone to treat secondary effluents will increase due to stricter quality requirements for water discharges, water shortages, limited availability of water supplies and water reuse (Oneby et al., 2010). In 2012, the Eastern Treatment Plant of Melbourne Water upgrade its facilities to an advanced tertiary treatment, which includes ozone, biological filters, ammonia, UV light and chlorine (MelbourneWater, 2021a). It treats on average 330 million litres of Melbourne's sewage a day and, at the time, was considered the biggest ozone and UV producing facility in the southern hemisphere with an investment of $380m (MelbourneWater, 2021a; WaterTechnology, 2013). It is one of the few WWTPs in the world capable of treating all income to an acceptable standard for reuse, enabling a wider range of potential reuses than before (MelbourneWater, 2021b, 2021c).

More recently, ozonation has also been studied as a treatment for micropollutants, which are organic and inorganic chemicals whose presence at low concentrations (ng to µg/L) can negatively impact living organisms (Rousseau et al., 2021). These pollutants are present in urban wastewater and include metals, microplastics, pharmaceuticals, personal care products, among others (Rousseau et al., 2021). Although conventional WWTPs cannot remove these micropollutants effectively, ozonation has proved to be an effective alternative treatment (Knopp et al., 2016). For instance, Switzerland revised its water protection laws in 2016 to minimize the discharge of micropollutants from WWTPs, with the implementation of several full-scale ozonation for advanced treatments, following the footsteps of countries such as Germany and Canada (Kienle et al., 2022). Sweden has identified that the general removal of pharmaceuticals in its WWTPs is not enough and are studying different tertiary treatments, which include an ozonation step combined with sand filters and granular activated carbon (Baresel et al., 2020).

4 Materials and Methods

4.1 Experimental Set-Up

Ozonation experiments were conducted in a pilot scale equipment of 0.14 m^3 (Ozone Generator, Steriline, Pilota 1279) provided by De Nora (Milan, Italy). The equipment is composed by a continuous-flow bubble column reactor connected with an ozone generation system and an ozone gas destroyer, as represented in Figure 3. The ozone was generated with compressed air and was introduced in the bottom of the bubble column reactor in counter current with the water added to increase the mass transfer efficiency. Before entering the reactor, the secondary effluent goes through a sand filter. After treatment, the effluent is withdrawn, and the remaining ozone goes to a gas destroyer.

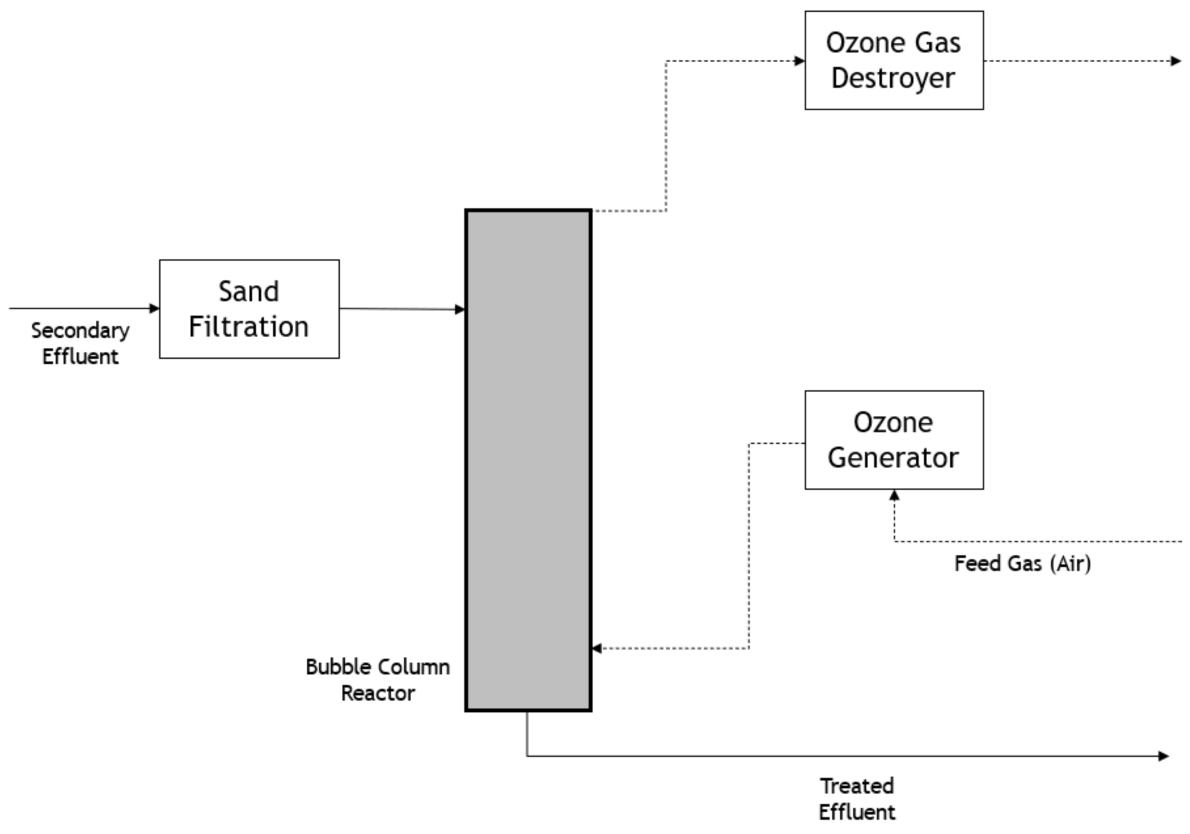

Figure 3 - Schematic diagram of the pilot-plant ozonation system at Gaia Litoral WWTP.

A typical ozone generation system with air is described in Figure 4 with more detail. It includes an air feeding blower, an air-cooling unit, a dehumidifier and the ozone generator (Magara et al., 1995). It was used a non-thermal plasma system that used electrical discharges to generate ozone. In these systems, the energy is mainly used for generating highly energetic electrons, promoting oxidation, enhancing molecular dissociation or producing free radicals, which can be used for ozone generation (Pekárek, 2003). The ozone destructor unit is a thermal-based system, where the vent gases are heated to around 400 °C, which drastically reduces the ozone half-life and accelerates its decomposition (Batakliev et al., 2014).

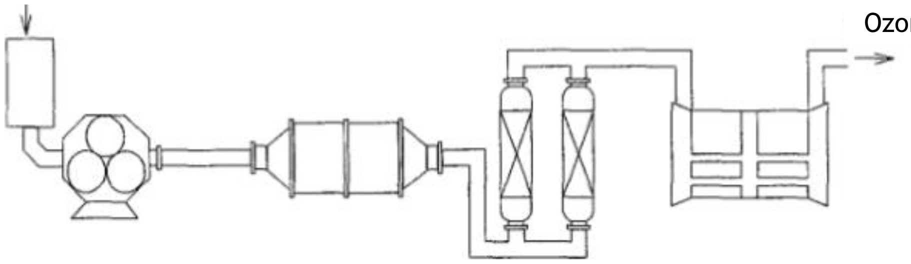

Figure 4 – Scheme of a general ozone generation system (Magara et al., 1995).

The tests were conducted with different HRT and TOD to evaluate its impact on the disinfection performed. The goal was to test three different HRT (2, 4 and 5.5 minutes), that depend on the water flowrate and water volume. As the water flowrate was determined by the sand filtration, three different volumes were achieved inside the reactor, by altering the water height. The TOD were obtained according to Equation 11:

$$TOD = \frac{Q_{gas}}{Q_{liq}} \times ([O_3]_{gas\,in} - [O_3]_{gas\,out}) \quad (11)$$

where, Q_{gas} and Q_{liq} are the gas and water flowrates, respectively, $[O_3]_{gas\ in}$ is the ozone concentration in the feed gas to the column and $[O_3]_{gas\ out}$ is the ozone concentration in the outlet gas of the column (Xu et al., 2002). The gas and water flowrate and additional operational conditions are represented in Table 6. The equipment did not allow the measurement of both ozone concentration in the feed gas and the outlet gas of the column. Therefore, to estimate the TOD it was also necessary to estimate both these parameters. It was possible to obtain the ozone concentration in the feed gas theoretically, according to the manufacturer's report. Given the operational conditions described in Table 6, it was possible to make a correlation between the electric current applied to the ozone generator and the ozone concentration in the feed gas (Table 7).

In the experiments, the concentrations used in the feed gas are the ones described in Table 7. For the estimation of the ozone concentration in the outlet gas of the column, a 40% mass transfer efficiency was considered, based on the data available in Xu et al. (2002), which studied the effect of the TOD in a similar set-up, with a continuous flow bubble column with ozone in counter-current. Samples of the treated effluent were collected, after three to five times the HRT tested, allowing the system to reach steady state. One to eight samples were analysed for each ozone concentration, for an HRT of 2 min.

Table 6 - Operational conditions of the bubble reactor column used for the ozonation experiments.

Reactor diameter (m)	0.35
Reactor height (m)	1.5
Volume (m^3)	0.14
Water flow rate (m^3/h)	1.2
Gas flow rate (m^3/h)	0.70
Inlet pressure gas vessel (bar)	1.0

Table 7 – Correlation between the current applied and the theoretical ozone concentration.

Current (A)	1.12	1.40	1.77	1.95	2.15	2.73
Ozone concentration (mg/L)	28.8	46.2	66.9	73.0	78.8	88.5

4.2 Water Analysis

Several water parameters were analysed. The ammonium, nitrogen and phosphorous analysis were performed according to the Spectroquant Ammonium Cell Test kit 114559, the Spectroquant Nitrogen (total) Cell Test kit 114763, and the Spectroquant Phosphate Cell Test kit 114729, respectively, all from Merck KGaA, (Darmstadt, Germany). The residual ozone measurements were conducted with the Merck Ozone Test 100607. The TSS analysis was performed according to the Standard Methods for the Examination of Water and Wastewater 2540 D (SMEWW, 2018). The BOD_5 was measured with the WTW OxiTop® BOD protocol, the pH with the Phoenix EC-30, the turbidity with the Bach 2100Qis Portable Turbidimeter and the transmittance with the Merck Spectroquant® Prove 600.

The detection of total coliforms and *E. coli* was performed using the Colilert-18 method (IDEXX, Maine, USA), which uses a Defined Substrate Technology (DST) with O-nitrophenyl-beta-D-galactopyranoside (ONPG) and 4-Methylumbelliferone Glucuronide (MUG) as indicators. It allows for the detection of coliforms that use ß-galactosidase to metabolize ONPG and change it from colourless to yellow and for the detection of *E. coli* that use ß-glucuronidase to metabolize MUG and create fluorescence. The Colilert-18 IDEXX reagent was added to 100 mL of each sample. Different dilutions were conducted based on the expected total coliforms and *E. coli* concentrations. The samples were poured into Quanti-Tray or Quanti-Tray/2000, sealed in Quanti-Tray Sealer and incubated at 36 ± 1 ºC for 18-20 hours. After incubation, the number of yellow and fluorescent wells was counted, and the Most Probable Number (MPN) of coliforms and *E. coli* was obtained with the IDEXX Water MPN Generator.

4.3 Risk Assessment

4.3.1 Public Health Risk Assessment

The development of a project for water reuse must comply with the appropriate legislation. In Portugal, the APA developed the "Guide for Non-potable Water Reuse" that provides guidelines for licensing of production and use of water for reuse and guidelines for risk assessment and management. The method described by the APA is further detailed in this subsection (APA, 2019).

Health risk assessment starts with hazard identification, which consists of identifying agents with the potential to cause an adverse effect on public health. The APA guidelines for public health risk assessment identified the concentration of *E. coli* in the water as the hazard to be considered. Although there are several identified microorganisms that can be present in these waters and cause several diseases, in the risk assessment process reference pathogens of particular relevance are chosen (typically *E. coli*), which is an indicator of faecal contamination (Collivignarelli et al., 2017). Different hazard levels depend on the *E. coli* concentration, according to Table 8. The attributed importance factors will be used in the appropriate equations to calculate the risk associated with the project.

Table 8 – Hazard levels for *E. coli* concentration in water (APA, 2019).

Hazard Level	*E. coli* Concentration (CFU/100 mL)	Importance Factor
V	*E. coli* ≥ 10^4	9
IV	10^3 < *E. coli* < 10^4	7
III	10^2 < *E. coli* < 10^3	5
II	10 < *E. coli* < 10^2	3
I	*E. coli* ≤ 10	1

For the development of the risk assessment analysis according to the APA guidelines, exposure routes and receptors must also be identified. The exposure routes considered are ingestion, inhalation or dermal adsorption, which can occur through direct contact with the water or indirect contact, through animals or vegetation (Rebelo et al., 2020). To each exposure route correspond different importance factors, according to the WHO (2006), as described in Table 9. For each receptor (*e.g.*, children or adults), each possible scenario of contact with the reused water should be described, which is a critical step in this process. These scenarios should be as detailed as possible, considering the exposure routes and the characteristics of each application. Importance factors can also be attributed to the different exposure scenarios, as described in Table 10 (Rebelo, 2018).

Table 9 - Importance factors applicable to each exposure routes to the treated water (Rebelo et al., 2020).

Exposure Route	**Importance Factor ($f_{i\ route}$)**	**Observations**
Ingestion	9	Is always considered as absolute importance.
Inhalation	9	Absolute importance in sprinkling irrigation systems.
	5	Essential or strong importance in other irrigation systems
Dermal adsorption	3	Weak importance due to the less evidence data of infection.

Table 10 - Importance factors for exposure scenarios to the treated water (Rebelo et al., 2020)

Importance Factor ($f_{i\ scenario}$)	**Exposure Scenario**
9	Exposure scenario with very high evidence of occurrence.
7	Exposure scenario with high evidence of occurrence.
5	Exposure scenario with medium evidence of occurrence.
3	Exposure scenario with low evidence of occurrence.
1	Exposure scenario with no evidence of occurrence.

The vulnerability of each receptor, V_r, can be determined based on the importance factors for exposure routes and exposure scenarios, according to Equation 12 (Rebelo, 2018):

$$V_r = \frac{\sum(f_{i\,route} \times f_{i\,scenario})}{f_{exposure}} \tag{12}$$

where, $f_{i\,route}$, corresponds to the importance factor of each exposure route considered, $f_{i\,scenario}$, corresponds to the importance factor of each exposure scenario considered, and $f_{exposure}$, corresponds to a normalization factor that can be obtained with Equation 13:

$$f_{exposure} = f_{max} \times \sum(f_{i\,route} \times n_{scenario}) \tag{13}$$

where, f_{max}, corresponds to the maximum value of the importance factors ($f_{max} = 9$), and $n_{scenario}$ corresponds to the number of exposure scenarios described for each receptor.

After the identification and classification of each exposure route and scenario, the use and application of physical or chemical barriers should be considered to reduce the contact of the receptor with the water through all routes. The barriers can be applied in different stages of the system, such as treatment, distribution, storage, or application. The use of disinfection, physical barriers, or access control to areas where the water was used are examples that can be used to allow a microbiological reduction. An equivalent barrier may be defined according to ISO 16075-2:2015 as a control measure that can be equivalent to a determined microbiological reduction (ISO, 2015b). The rupture or failure of the installed barriers caused by possible adverse events needs to be accounted for and is represented by the calculation of the damage. The use of several barriers in the different stages of the system, reduces the probability of these adverse events. Some of the most common are non-compliance with the quality standards due to failures with treatment, distribution or storage, incorrect use, and accidental exposure to the water. The probability of such events can be defined empirically from rare to almost certain. The severity of the damages caused by such scenario also needs to be considered and can be defined empirically from insignificant to severe, as described in Table 11.

Table 11 - Probability of adverse event that cause failure in barrier (APA, 2019).

Probability	Description
Rare	Never occurred in the past and is highly unlikely that can occur in a reasonable period.
Unlikely	Never occurred in the past but can occur under exceptional circumstances in a reasonable period.
Possible	May have occurred in the past and/or can occur in normal circumstances in a reasonable period.
Likely	There are records of such events in the past and is likely that it will occur again in a reasonable period.
Almost certain	There are records of such events in the past and/or is almost certain it can occur in most circumstances in a reasonable period.

The same scale can be applied to the severity of the damages. For the determination of the damage, a matrix can be applied as exemplified in Table 12, in which the value of each cell, d_i, is obtained according to Equation 14 (Rebelo, 2018):

$$d_i = \frac{\text{damage severity} \times \text{probability of barrier failure}}{5} \tag{14}$$

The matrix represented in Table 12 can be normalized by importance factors, as demonstrated in Table 13. This normalization improves the results obtained in Table 12, by including random uncertainties that cannot be quantified (Rebelo, 2018), producing the normalized matrix represented in Table 14.

Table 12 - Damage determination matrix associated with the probability of barrier failure and severity (APA, 2019).

			Rare	**Unlikely**	**Possible**	**Likely**	**Almost Certain**
			Probability of barrier failure				
			1	**2**	**3**	**4**	**5**
Insignificant	**Severity**	**1**	0.2	0.4	0.6	0.8	1.0
Minor		**2**	0.4	0.8	1.2	1.6	2.0
Moderate		**3**	0.6	1.2	1.8	2.4	3.0
Major		**4**	0.8	1.6	2.4	3.2	4.0
Severe		**5**	1.0	2.0	3.0	4.0	5.0

Table 13 - Damage normalization for importance factor determination (Rebelo, 2018).

Damage (d_i)	**Importance factor (f_i)**
$d_i \leq 0.5$	1
$0.5 \leq d_i < 1$	2
$1 \leq d_i < 1.2$	3
$1.2 \leq d_i < 2$	4
$2 \leq d_i < 2.4$	5
$2.4 \leq d_i < 3$	6
$3 \leq d_i < 3.2$	7
$3.2 \leq d_i < 4$	8
$d_i \geq 4$	9

Table 14 - Normalized damage matrix for public health risk assessment (Rebelo, 2018).

			Rare	Unlikely	Possible	Likely	Almost Certain
			Probability of barrier failure				
			1	2	3	4	5
Insignificant	Severity	1	1	1	2	2	3
Weak		2	1	2	4	4	5
Moderate		3	2	4	4	6	7
Major		4	2	4	6	8	9
Severe		5	3	5	7	9	9

The total damage, *D*, can be obtained from the damage of each scenario and is determined according to Equation 15:

$$D = \frac{\sum(d_i \times n_i)}{f_{max} \times n_{barrier}} \quad (15)$$

where n_i is equal to the number of equivalent barriers in place.

The risk associated with each receptor, $R_{receptor}$, is a product of the hazard, vulnerability, and damage, and is given by Equation 16:

$$R_{receptor} = H \times V_r \times D \quad (16)$$

where, *H*, corresponds to the hazard level classification obtained from Table 8.

The global public health risk associated with a project for wastewater reuse, R_{PH}, can be obtained according to Equation 17:

$$R_G = \frac{\sum R_{receptor}}{n_{receptor}} \quad (17)$$

where $n_{receptor}$ represents the total number of receptors. The value for the global risk for public health is in a range from above 0 to a maximum of 9 and can be expressed in three different levels: negligible if below 3, acceptable if equal or above 3 and below 7, and unacceptable if equal or above 7. There is always a risk associated with using treated urban wastewater - the risk is always higher than zero. The level obtained must be negligible or acceptable, otherwise the project is not viable and the process must be reviewed with the application of new barriers (Rebelo, 2018).

4.3.2 Environmental Risk Assessment

The risk of wastewater reuse also needs to be assessed for the environment, namely the surface and groundwater resources. In hydrogeologic sensitive zones, the presence of nitrogen (N), phosphorus (P), and emerging pollutants should be considered in the risk assessment development. The microbiologic content should also be considered, particularly in bathing and aquaculture areas and zones where water for human consumption exists. Different concentrations of N and P can be attributed to different hazard levels, as represented in Table 15 similarly to Table 8 for *E. coli* concentration.

Table 15 - Hazard levels for the concentration of N and P (APA, 2019).

Hazard Level	**Concentration** (mg/L)	**Classification**
V	N > 15 and P >3	9
IV	N ≤ 15 or P ≤ 3	7
III	N ≤ 15 or P ≤ 3	5
II	N ≤ 10 and P ≤ 3	3
I	N ≤ 5 and P ≤ 0.5	1

In zones vulnerable for nitrate pollution or eutrophication the hazard level considered for N and P should be IV, respectively.

The risk characterization on the water resources in this work followed a semi-quantitative approach, due to the lack of data to support a quantitative approach. This methodology is also based on the importance scales proposed by Saaty (1980). In this case, the vulnerability will be obtained with the conjugation of a matrix that considers the water resources' own characteristics for superficial and underground waters, with the exposure scenarios and number of barriers considered. A matrix for the vulnerability of the water resources based on its characteristics is described in ISO 16075-1:2015 and represented in Table 16 (ISO, 2015a). From this table, it is possible to obtain the partial vulnerabilities for superficial, V_{sup}, and underground, V_{under}, waters.

Table 16 - Matrix for risk characterization of water resources (APA, 2019).

Infiltration in Underground Water			**No Infiltration**	**Low Infiltration**	**Medium Infiltration**	**High Infiltration**
			I	**II**	**III**	**IV**
Risk for Underground Water	**Superficial aquifer without clay layer**	**I**	2	4	6	6
	Deep aquifer with clay layer	**II**	2	4	4	6
	Deep aquifer with significant clay layer	**III**	2	2	4	4
	No aquifer in the area	**IV**	2	2	4	4
Risk for Superficial Waters			6	6	4	2
			IV	III	II	I
			High Superficial Run-Off	Medium Superficial Run-Off	Low Superficial Run-Off	No Superficial Run-Off
			Superficial Run-Off			

The water resources vulnerability, V_{wr}, can be obtained with Equation 18:

$$V_{wr} = V_{under} \times \frac{V_{under}}{V_{under} + V_{sup}} + V_{sup} \times \frac{V_{sup}}{V_{under} + V_{sup}} \quad (18)$$

It is possible to obtain four different values for the water resources vulnerability, which correspond to different importance levels, according to Table 17.

Table 17 - Importance factors for water resources vulnerability (APA, 2019).

V_{WR}	$V_{WR\ i}$
5.2	9
5.0	7
4.0	5
3.3	3

The global vulnerability, V_G, will also depend on the barriers applied and the exposure scenarios considered. The risk assessment for water resources, like the public health risk assessment, also considers the use of barriers as a prevention method. However, the equivalent barrier concept does not apply, so each barrier corresponds to one prevention method. Some typically used barriers include systems for partial or total retention and for leakage detection. The description of possible adverse events that may cause a failure of the installed barriers is similar to the one described in section 4.3.1. The barriers considered and the respective importance levels are represented in Table 18.

Table 18 - Barriers applied and importance factors (APA, 2019).

Barrier	Importance Factor ($f_{i\ barrier}$)
Lack of barriers	9
Leakage detection system	7
Partial retention capacity / adequate irrigation system for water needs	5
Full retention capacity	3

For each exposure route, one or two barriers can be applied, corresponding to one or two exposure scenarios, as represented in Table 19.

Table 19 – Number of exposure scenarios (APA, 2019).

Barrier		Number of Exposure Scenarios ($n_{scenario}$)
Exposure Route	Lack of barriers	1
	Leakage detection system	1
	Partial retention capacity / adequate irrigation system for water needs	1
	Full retention capacity	1
	Leakage detection system Partial retention capacity / adequate irrigation system for water needs	2
	Leakage detection system Full retention capacity	2

The global vulnerability, V_G, can be calculated according to Equation 19:

$$V_G = V_{wr} \frac{\sum f_{i\ barrier}}{f_{max} \times n_{scenario}} \quad (19)$$

where $f_{i\ barrier}$ represents the importance factor associated with each barrier.

The damage determination can be obtained by Equation 15 which depends on the probability of exposure of the water resources to contamination and the severity. Table 20 and Table 21 represent the definition of the probability of exposure and the severity of the damage, respectively.

Table 20 - Probability of exposure of the water resources to contamination (APA, 2019).

Probability of Exposure	Value	Contamination Route
Almost Certain	5	Demonstrated
Likely	4	Possible
Possible	3	Eventual
Unlikely	2	Lack of data

Table 21 - Damage severity for water resources (APA, 2019).

Damage Severity	Value	Water Quality
Severe	5	Below good
Major	4	Good with defined use and classification (vulnerable to nitrate pollution or sensitive)
Moderate	3	Good with defined use or classification (vulnerable to nitrate pollution or sensitive)
Weak	2	Good without defined use or classification

A normalized determination matrix similar to the one conducted in the public health risk assessment can be applied, as represented in Table 22.

Table 22 - Normalized damage matrix for environmental risk assessment (APA, 2019).

			Unlikely	**Possible**	**Likely**	**Almost Certain**
			Probability of Exposure			
			2	**3**	**4**	**5**
Weak	**Severity**	**2**	2	4	4	5
Moderate		**3**	4	4	6	7
Major		**4**	4	6	8	9
Severe		**5**	5	7	9	9

The total damage, *D*, can be determined according by Equation 15. The global risk for the water resources, R_{WR}, can be obtained according to Equation 20:

$$R_{WR} = \frac{H \times V_G \times D}{9} \tag{20}$$

where *H* represents the hazard level classification according to Table 8 and Table 15. The values of the water resources risk mimic the risk for public health, with the same three levels of acceptance. Similarly, the level obtained must be negligible or acceptable, otherwise the project is not viable (Rebelo, 2018).

5 Results and Discussion

5.1 Ozonation

Several HRTs and TODs were experimented. The results for the different HRTs (2.0, 4.0 and 5.5 min) are shown in Table 23. The results represent the faecal coliforms and *E. coli* concentration after the ozonation treatment and its logarithmic reduction, which was obtained according to Equation 21:

$$Log\ red = \log\frac{N_0}{N} \qquad (21)$$

where N_o is the initial concentration of faecal coliforms or *E. coli,* and N is the respective concentration after the treatment.

Initially, tests were conducted to understand the influence of the HRT in the ozone treatment, by comparing the results for the total coliforms and *E. coli* concentrations, for the same TOD and different HRT, for each day. As observed from Table 23, for the samples taken on April 8th, 2022, the results obtained for an HRT of 5.5 min present slightly lower concentrations of total coliforms, comparing to 4.0 min. For the results obtained for *E. coli,* it was not possible to make a direct comparison at a TOD of 21.8 mg/L, as the *E. coli* concentration at an HRT of 5.5 min was under the detection limits of the method with the dilution used. For a TOD of 19.4 mg/L, the *E. coli* concentrations at an HRT of 4 min and 5.5 min were equal. For the samples taken on April 12th, 2022, the results obtained are similar for HRTs of 4.0 min and 2.0 min, with 2.0 min presenting the highest log reduction for both total coliforms and *E. coli*.

As expected according to literature, the HRT was not a critical parameter in the ozonation treatment (Paraskeva & Graham, 2005). Xu et al. (2002) reported that an HRT of 2 min would provide the same inactivation as longer HRTs, because of the high kinetic rate of bacteria with ozone. Due to limitations regarding the time and resources required to obtain more data points, it was not possible to perform more tests that would lead to a more robust decision. With the available literature and data points, it was chosen an HRT of 2.0 min to further testing the system at different TODs.

Table 23 – The effects of HRT in faecal coliforms and *E. coli* concentration.

Date	**HRT** (min)	**TOD** (mg/L)	**FC conc.**	**Log. red. FC**	***E. coli* conc.**	**Log. Red. *E. coli***
8/04	5.5	19.4	990	3.24	200	2.99
8/04	5.5	21.8	100	4.24	< 100	-
8/04	4.0	19.4	3240	2.73	100	3.29
8/04	4.0	21.8	1110	3.19	100	3.29
12/04	4.0	19.4	164	4.02	31	4.27
12/04	4.0	21.8	99	4.24	20	4.46
12/04	2.0	19.4	137	4.10	31	4.27
12/04	2.0	21.8	64	4.43	10	4.76

- Not determined, as the *E. coli* concentration was under the detection limits of the method for the dilution of 1/100.

FC – faecal coliforms; HRT – hydraulic residence time; TOD – transferred ozone dose.

After the determination of the HRT to be used, samples for different TODs (7.1 mg/L, 11.4 mg/L, 16.4 mg/L, 17.9 mg/L, 19.4 mg/L and 21.8 mg/L) were collected and analysed for both faecal coliforms and *E. coli*. All the results obtained for the collected samples are present in Appendix A. Samples Collected.

The results presented in Figure 5 show that for TODs comprehended between 7.1 mg/L and 16.4 mg/L there is a slight increase in the *E. coli* logarithmic reduction with an increase of the TOD. From a TOD 16.4 of mg/L to 17.9 mg/L there is a significant increase in the *E. coli* logarithmic reduction that then slightly increases and stabilises for TODs of 19.4 mg/L and 21.8 mg/L. In Figure 6 it is possible to observe that for TODs equal or higher than 17.9 mg/L all the samples had *E. coli* concentrations below 100 CFU/100 mL and some samples below 10 CFU/100 mL. Paraskeva and Graham (2005) tried to apply a linear regression to model the logarithmic reduction of *E. coli* and total coliforms as a function of the TOD and a similar trend seems to be found in different literature (Gehr et al., 2003; Xu et al., 2002). The results obtained do not seem to follow a linear trend and there are no reports of two distinct regions in the graphs, however more information and samples collected would be helpful to verify this statement.

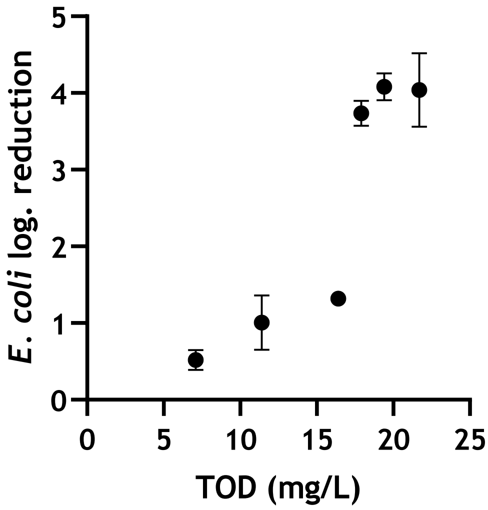

Figure 5 – Performance of the ozone for *E. coli* reduction, for an HRT of 2.0 min.

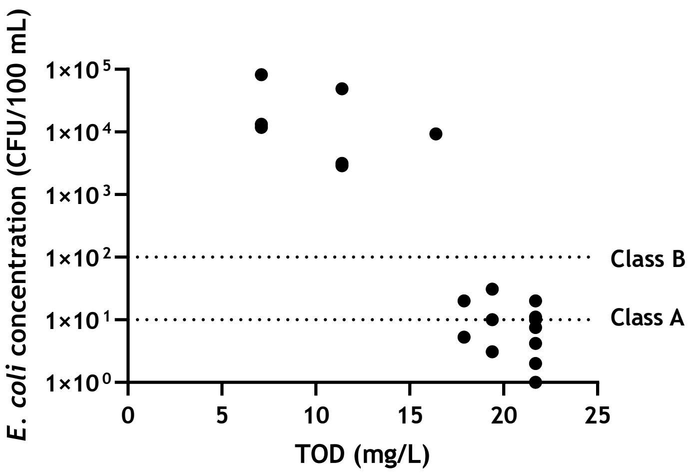

Figure 6 – *E. coli* concentration after ozone treatment, for an HRT of 2.0 min.

An important parameter to control is the residual ozone in the water after the ozone treatment, which is measurable after the ozone demand of the water is met (Paraskeva & Graham, 2005). The ozone demand is considered as the amount of oxidizable material in the water. Xu et al. (2002) determined the initial ozone demand of an effluent by measuring residual ozone concentration for TODs up to 40 mg/L. For lower TODs, the residual ozone was almost negligible (below 0.4 mg/L) and from a TOD of 8 mg/L it tends to increase linearly, reaching concentrations of 16 mg/L for a TOD of 40 mg/L and an HRT of 2.0 min (Xu et al., 2002). Xu et al. (2002) also reported that the TOD necessary to reach the ozone demand depends on the effluent to be treated, particularly its organic content. In this work, the results obtained for the residual ozone measured in the water for the different TODs are represented in Figure 7. As expected, the residual ozone tends to increase with an increase of the TOD, varying between 0.08 mg/L for a TOD of 7.1 mg/L and 0.16 mg/L for a TOD of 21.8 mg/L, which can be considered negligible. Therefore, it was not possible to determine the ozone demand of the treated water, since the residual ozone concentration remained very low for all the TODs tested.

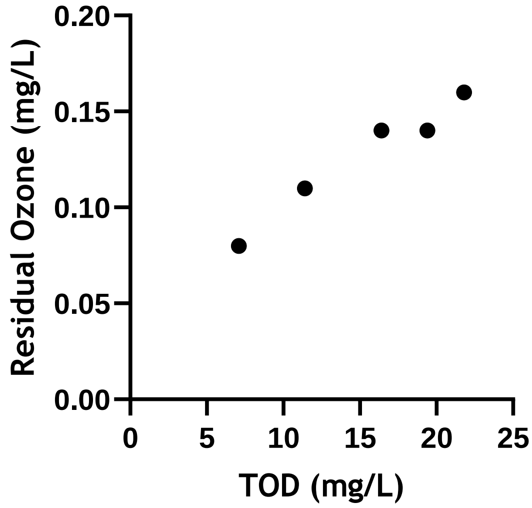

Figure 7 - Residual ozone concentration in the effluent after the ozonation treatment, for an HRT of 2.0 min.

To choose the ideal TOD to be applied to the system, different values were tested. However, due to time and resources limitations, the number of replicas achieved for each TOD was not constant. The TOD chosen to be further tested was 21.8 mg/L, since it showed a higher potential in achieving *E. coli* concentrations below 10 CFU/100 mL. For this TOD, it was also measured different quality parameters of the treated effluent, as represented in Table 24. It is possible to understand that the main impact of the ozonation process is related to a significant reduction of both faecal coliforms and *E. coli,* although there is also an increase in the transmittance. These results are aligned with the available literature that predicted and reported colour removal as the most significant impact of an ozone treatment, other than disinfection (Drinan & Spellman, 2012; Xu et al., 2002). The water from the sand filtration already presents acceptable values of BOD_5, TSS and turbidity for class A water and, consequently, for every other class, as previously reported, and did not suffer significant change in these parameters after the ozonation treatment. The European Union regulation on the minimum requirements for water reuse states that the values of *E. coli* must be met in 90% or more of the samples and that none should exceed the maximum deviation of 1 log unit from the indicated value for each water class represented in Table 1 (EU, 2020). Although some samples at a TOD of 17.9 mg/L, 19.4 mg/L and 21.8 mg/L present values for *E. coli* concentration equal or below to 10 CFU/100 mL, this concentration could not be met in 90% or more of the samples, so it was not possible to produce water that meets the requirements for class A. On the other hand, for these three TODs, an *E. coli* concentration equal or below to 100 CFU/100 mL was always met, so it was possible to produce water that meets the requirements for class B.

Table 24 – Water parameters for samples tested at a TOD of 21.8 mg/L.

Parameter	After sand-filtration	After ozone treatment
pH	7.2 ± 0.1	7.27 ± 0.08
Temperature (ºC)	19.3 ± 0.8	20 ± 1
BOD_5 (mg/L)	5 ± 1	6 ± 2
TSS (mg/L)	3 ± 1	3 ± 1
Turbidity (NTU)	1.4 ± 0.2	1.1 ± 0.2
E. coli (CFU/100 mL)	(4 ± 2) x 10^4	6 ± 4
NH_4^+ (mg/L)	52 ± 7	52 ± 8
N (mg/L)	53 ± 6	54 ± 6
P (mg/L)	0.5 ± 0.2	0.6 ± 0.2
Transmittance (%)	53 ± 1	66 ± 1
Faecal Coliforms	(4 ± 2) x 10^4	50 ± 40

The TODs that present *E. coli* concentrations below 100 CFU/100 mL are within the range of the values typically studied and used at current WWTP's, as represented in Table 4 and Table 5. They are also similar to the ones reported by Xu et al. (2002) for similar coliforms concentration. These values depend on different effluent characteristics, different legislation or end-use of the effluent after ozonation. The use of higher TODs implies higher costs, so a fit-for-purpose approach is recommended. With the available data, the use of a TOD of 17.9 mg/L would be sufficient to produce class B water, while higher doses do not produce class A water. For these reasons, a TOD of 17.9 mg/L would be the suggested dose to apply in this WWTP. A cost analysis would be necessary to understand the economic viability of the treatment. However, this assessment was not possible due lack of data provided by the equipment supplier.

5.2 Health Risks associated with water reuse

As previously mentioned, there were several opportunities of application for the reuse of treated water identified by the company such as irrigation of public parks, crops and golf courses and pavement and vehicle washing. The most significant application identified was public park irrigation and the risk assessment analysis will focus on this situation. It was considered the use of a sprinkling irrigation system with irrigation schedule for early morning and late afternoon or evening. The receptors identified were the maintenance workers responsible for the upkeep of the irrigation system and the users of the park, considering both adults and children. Table 25 to Table 30 present the routes and scenarios identified and their classification and justification for each receptor. The scenarios identified for each receptor are similar, however, they may represent different classification for different receptors. The irrigation schedule reduces the exposure for its users, both adults and children, given that visits are not expected to the park at this time. For this reason, lower importance factors were attributed for these receptors when compared to the maintenance workers, which deal directly with the irrigation system and are more susceptible to contact with the treated water (Rebelo et al., 2020). It was also considered that previous studies found that children are more prone for gastrointestinal diseases from water borne pathogens than adults and tend to present more unpredictable behaviours that can pose higher risks for their health (Colford Jr et al., 2007; Russo et al., 2020). For these reasons, higher importance factors were attributed for children than for adults. The classification of each scenario for each receptor is further explained in Table 25 to Table 30 and is based on the APA guidelines and the available literature.

Table 25 – Description and classification of the exposure scenarios to the treated water for the maintenance workers.

Exposure Scenario	Exposure Route	Scenario Explanation	$f_{i\ scenario}$	Importance Factor Justification
Intentional water uptake	Ingestion	A worker can intentionally ingest water from the system	5	This scenario does not seem likely given the required training for the workers and signalling of non-potable water. However, this is a pathway with demonstrated infection data and a scenario that, although unlikely, depends on human behaviour so it is considered as medium importance (APA, 2019).
Ingestion of droplets during leaks	Ingestion	Some leaks may form droplets if the irrigation system is under pressure that can be ingested	9	This is a probable scenario, considering a sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of absolute importance (Rebelo et al., 2020).
Ingestion of droplets from the contact with wet vegetation	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	9	This is considered a demonstrated pathway of absolute importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from the contact with irrigation system	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	9	This is considered a demonstrated pathway of absolute importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with wet clothes	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	9	This is considered a demonstrated pathway of absolute importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with domestic animals	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	9	This is considered a demonstrated pathway of absolute importance (Rebelo et al., 2020; Russo et al., 2020).
Intentional ingestion of soil	Ingestion	An adult can intentionally ingest soil	5	This scenario does not seem likely given the required training for the workers and signalling of non-potable water. However, this is a pathway with demonstrated infection data and a scenario that, although unlikely, depends on human behaviour so it is considered as medium importance (Rebelo et al., 2020).
Non-intentional ingestion of soil	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	9	This is considered a demonstrated pathway of absolute importance. Possible after contact with wet soil (Rebelo et al., 2020).

Table 26 – Description and classification of the exposure scenarios to the treated water for the maintenance workers *(cont)*.

Exposure Scenario	Exposure Route	Scenario Explanation	f_i scenario	Importance Factor Justification
Inhalation of aerosols	Inhalation	Some leaks may form aerosols that can be inhaled	9	This is a probable scenario, considering sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of absolute importance and there is evidence of *legionella* transmission through inhalation of water aerosols (Dyke et al., 2019).
Inhalation of micro droplets from domestic animals	Inhalation	Pathogens can be inhaled from contact with domestic animals (*e.g.*, dogs shake off)	4	This a scenario that can occur, but there is no significant evidence, so it is considered an importance factor between medium and weak (APA, 2019; Rebelo et al., 2020).
Contact with wet irrigation system	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	3	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use personal protective equipment (PPE) and are aware of the risk associated with water for reuse, so this scenario is considered of weak importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet soil or vegetation	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	3	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of weak importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet clothes	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	3	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of weak importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with domestic animals	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	3	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of weak importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).

Table 27 - Description and classification of the exposure scenarios to the treated water for the adult users of the park.

Exposure Scenario	Exposure Route	Scenario Explanation	f_i scenario	Importance Factor Justification
Intentional water uptake	Ingestion	An adult can intentionally ingest water from the system	5	This is a pathway with demonstrated infection data and a scenario that, although unlikely, depends on human behaviour so it is considered as medium importance (APA, 2019).
Ingestion of droplets during leaks	Ingestion	Some leaks may form droplets if the irrigation system is under pressure that can be ingested	7	This is a probable scenario considering a sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020).
Ingestion of droplets from the contact with wet vegetation	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	7	This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from the contact with irrigation system	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	7	This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with wet clothes	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	7	This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with domestic animals	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	7	This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020; Russo et al., 2020).
Intentional ingestion of soil	Ingestion	An adult can intentionally ingest soil	5	This scenario does not seem likely given the required signalling of non-potable water. However, this is a pathway with demonstrated infection data and a scenario that, although unlikely, depends on human behaviour so it is considered as medium importance (Rebelo et al., 2020).
Non-intentional ingestion of soil	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	7	This is considered a demonstrated pathway of strong importance. Possible after contact with wet soil (Rebelo et al., 2020).
Inhalation of aerosols	Inhalation	Some leaks may form aerosols that can be inhaled	9	This is a probable scenario considering a sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of absolute importance and there is evidence of *legionella* transmission through inhalation of water aerosols (Dyke et al., 2019).

Table 28 - Description and classification of the exposure scenarios to the treated water for the adult users of the park (*cont*).

Exposure Scenario	Exposure Route	Scenario Explanation	f_i scenario	Importance Factor Justification
Inhalation of micro droplets from domestic animals.	Inhalation	Pathogens can be inhaled from contact with domestic animals (*e.g.*, dogs shake off).	4	This a scenario that can occur, but there is no significant evidence, so it is considered an importance factor between medium and weak (APA, 2019; Rebelo et al., 2020).
Contact with wet irrigation system.	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface.	1	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of low importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet soil or vegetation.	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface.	1	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of low importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet clothes.	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface.	1	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of low importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with domestic animals.	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface.	1	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered of low importance (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).

Table 29 - Description and classification of the exposure scenarios to the treated water for the child users of the park.

Exposure Scenario	Exposure Route	Scenario Explanation	f_i scenario	Importance Factor Justification
Intentional water uptake	Ingestion	A child can intentionally ingest water from the system	9	This is a pathway with demonstrated infection data and is considered of absolute importance due to unpredictable children behaviour (APA, 2019).
Ingestion of droplets during leaks	Ingestion	Some leaks may form droplets if the irrigation system is under pressure that can be ingested	8	This is a probable scenario considering a sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of strong importance (Rebelo et al., 2020).
Ingestion of droplets from the contact with wet vegetation	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	8	This is considered a demonstrated pathway between absolute and strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from the contact with irrigation system	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	8	This is considered a demonstrated pathway between absolute and strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with wet clothes	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	8	This is considered a demonstrated pathway between absolute and strong importance (Rebelo et al., 2020; Russo et al., 2020).
Ingestion of droplets from contact with domestic animals	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	8	This is considered a demonstrated pathway between absolute and strong importance (Rebelo et al., 2020; Russo et al., 2020).
Intentional ingestion of soil	Ingestion	A child can intentionally ingest soil	9	This is a demonstrated pathway of absolute importance due to unpredictable children behaviour (Rebelo et al., 2020).
Non-intentional ingestion of soil	Ingestion	Water-borne pathogens can be transferred by hand mouth-face contact	8	This is considered a demonstrated pathway between absolute and strong importance. Possible after contact with wet soil (Rebelo et al., 2020).

Table 30 - Description and classification of the exposure scenarios to the treated water for the child users of the park (*cont*).

Exposure Scenario	Exposure Route	Scenario Explanation	f_i scenario	Importance Factor Justification
Inhalation of aerosols	Inhalation	Some leaks may form aerosols that can be inhaled	9	This is a probable scenario given that it is considered a sprinkling irrigation system exposed to the environment. This is considered a demonstrated pathway of absolute importance and there is evidence of *legionella* transmission through inhalation of water aerosols (Dyke et al., 2019).
Inhalation of micro droplets from domestic animals	Inhalation	Pathogens can be inhaled from contact with domestic animals (*e.g.*, dogs shake off)	5	This a scenario that can occur, but there is no significant evidence, so it is considered a medium importance factor (APA, 2019).
Contact with wet irrigation system	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	2	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered with importance between weak and low (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet soil or vegetation	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	2	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered with importance between weak and low (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with wet clothes	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	2	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered with importance between weak and low (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).
Contact with domestic animals	Adsorption	Pathogens can be adsorbed by skin or transferred to eyes (hand-eye) by direct contact with wet surface	2	The transmission of water-borne pathogens through minimal contact or ocular exposure is not likely and workers use PPE and are aware of the risk associated with water for reuse, so this scenario is considered with importance between weak and low (Peng & Zhou, 2020; Rebelo et al., 2020; Russo et al., 2020).

With the available data in Table 25 to Table 30 it is possible to determine the vulnerability of each receptor, according to Equation 12. These results are presented in Table 31.

Table 31 - Vulnerability for each receptor, based on the importance factors for exposure routes and exposure scenarios described.

Receptor	**Vulnerability (V_r)**
Maintenance Workers	0.72
Park Users - Adults	0.59
Park Users - Children	0.79

For the determination of the health risk associated with the project for reuse, it is also necessary to consider the implementation of barriers to reduce the contact of the receptors with the water. They can be applied in different stages of the system and are used to allow for a microbiological reduction. The concept of equivalent barrier was adopted by the APA guidelines according to ISO (2015b), which states that a barrier can represent a determined logarithmic reduction. The barriers applied for the considered situation were the use of personal protective equipment (PPE) for maintenance workers and access control during irrigation for the users of the park. The likelihood of failure and its severity were classified and the normalized partial damage, d_i, for each barrier was obtained according to Table 12. The classification and justification for the results obtained are further detailed in Table 32. With these data and through the application of Equation 15 it was possible to obtain a total damage, D, of 1.

Table 32 – Barriers implemented, and damage associated with its failure.

Receptor	Barrier Type	Equivalent Barrier	Likelihood of Failure	Justification	Severity	Justification	Partial Damage (d_i)
Maintenance Worker	Use of PPE	1	4	It's a likely scenario as failures in PPE use due to personal behaviour are reported (Damalas & Abdollahzadeh, 2016).	5	This causes higher contact with water and is particularly relevant in maintenance works (Rebelo et al., 2020).	9
Adults	Access control during irrigation	1	5	It’s an almost certain scenario as in a public park all areas are accessible, even though the irrigation schedule (APA, 2019).	4	This causes higher contact with water although it is reported less evidence of illness due to minimal contact (Rebelo et al., 2020; Russo et al., 2020).	9
Children	Access control during irrigation	1	5	It’s an almost certain scenario as in a public park all areas are accessible, even though the irrigation schedule (APA, 2019).	4	This causes higher contact with water although it is reported less evidence of illness due to minimal contact (Rebelo et al., 2020; Russo et al., 2020).	9

Finally, before health risk could be calculated, it was necessary to define the hazard level, *H*. After the tests conducted with the ozone treatment available it was possible to assure an *E. coli* concentration between 10 and 100 CFU/100 mL which, according to Table 8 corresponds to a hazard level classification (*H*) of 3. The risk for each receptor, $R_{receptor}$, was obtained by Equation 16 and the global health risk, R_G, by Equation 17 and are shown in Table 33.

Table 33 - Health risk for each receptor for the water reuse project.

Receptor	Health Risk	Classification
Maintenance Workers	2.17	Negligible
Park Users - Adults	1.77	Negligible
Park Users - Children	2.37	Negligible
Global Risk	2.10	Negligible

The adult park users, which present a global health risk value of 1.77, are the receptors that present the lowest health risk, as expected, while the health risk obtained for the child park users was the highest, at 2.37. The maintenance workers presented a global health risk value of 2.17, which resulted in a global risk of 2.10. All the values obtained are below 3, as observed in Table 33. Therefore, the health risk is negligible for all the receptors and the global risk indicates that the situation considered for the irrigation of the public park in the described conditions is viable from a health risk perspective.

Another significant destination of the treated water could be the golf courses. The application of water for reuse in these facilities only requires class B water, so in this scenario, there would be no need for the application of barriers as in the irrigation of parks, although they should always be considered to minimise the risk. In this case, the scenarios identified, and its classification should be similar to the ones in this work, so if the same barriers are applied, it is expected the same outcome of negligible health risk for the project. For crop irrigation, other receptors and scenarios must be identified. The workers of the agricultural fields should present similar scenarios as the maintenance workers described. However, the users are no longer relevant, and the consumers must be taken in consideration. As proposed by Rebelo (2018) for an orange tree orchard, possible exposure scenarios include consumption of the crop, in this case fruit, but other raw or processed crops can be considered, ingestion of soil or contact with roots, leaves or fruits. Situations such as sun-dried crops before harvesting or how the crop is consumed (*e.g.*, orange is eaten without skin) can be considered barriers applicable for different cases of crop irrigation (APA, 2019; Rebelo, 2018). With the ozonation treatment studied, it would not be possible to reuse this water for pavement or vehicle washing (*e.g.*, vehicle cleaning at gas stations) since it requires a class A water, which could not be obtained. In these cases, the receptors considered should include the users of the washing system and its surroundings where the generation of aerosols can be critical (APA, 2019).

5.3 Environmental Risk

The hydrographic region that includes the Gaia Litoral WWTP and its surroundings has a basin area of approximately 45 km^2, located within the Douro River basin, and includes the municipalities of Vila Nova de Gaia, Gondomar and Porto (APA, 2016a). This region is not flagged as vulnerable for eutrophication or nitrate pollution and has a classification of “Good” for the general physical and chemical components of both its superficial and underground water (APA, 2014, 2016a, 2016b). In this scenario, according to Table 15, the hazard level classification, *H*, for both P and N its 5. As there are several water collection points in this aquifer for public supply, it is also necessary to consider the the hazard level classification for *E. coli*, which, with the proposed treatment is 3.

To evaluate the vulnerability of the water resources it would be necessary to collect data on the field of application to assess the degree of infiltration in the aquifer or the run-off at the surface. This data needs to be acquired in the appropriate application area for each water reuse project. Since this approach was meant as an example of application of the model, it was not possible to collect this data, so the maximum level of vulnerability for the water resources was considered as the worst-case scenario. Finally, in this situation it was not contemplated the application of any barrier which, according to Table 18, represents an importance factor, $f_{i\ barrier}$, of 9, so the probability of exposure is almost certain. Since the water quality is classified as "Good", there is no risk of eutrophication or nitrate pollution. Considering that there is a defined use for public supply as there are several water collection points in this aquifer for this purpose, according to Table 21 it will result in a moderate damage (APA, 2014, 2016a, 2016b). According to Table 22, it was possible to obtain the damage for each scenario, d_i, of 7 and, with Equation 15, to determine a total damage, D, of, approximately, 0.78. With Equation 19, a global vulnerability, V_G, of 9 was found. Using this data and Equation 20 it was obtained a global risk for the water resources, R_{WR}, of, approximately, 3.89 for the concentrations of P and N, which presents an acceptable risk and 2.33 for *E. coli* concentration, which presents a negligible risk. To apply this method to a practical situation it would be necessary to collect the data from the field and assess the application of different barriers, if possible. However, from the calculations made, it is possible to conclude that in this region with the proposed ozonation treatment, the risk for the environment will not be higher than 3.89, which will always present, at least, an acceptable risk. Lower values can be obtained depending on the characteristics of the field and the application of barriers.

6 Conclusion

Gaia Litoral WWTP intended to develop a treatment to allow treated water reuse for several applications. At the beginning of the project, the WWTP was only capable of producing class D water, due to its microbiological content. The goal was to achieve a water of, at least, class B, which represents a maximum *E. coli* concentration of 100 CFU/100 mL. An ozonation treatment was installed as a disinfection step. HRTs of 2.0 min, 4.0 min and 5.5 min were tested and resulted in similar disinfection. These results were expected, according to the literature consulted, so further samples were obtained for an HRT of 2.0 min. For TODs between 7.1 and 16.4 mg/L, there was a reduction in the faecal coliforms and *E. coli* concentration, however the *E. coli* concentration was always above 1000 CFU/100 mL, while for TODs between 17.9 and 21.8 mg/L, there was a more significant disinfection of the water, with *E. coli* concentrations below 100 CFU/100 mL for every sample. In fact, 75% of the samples obtained at a TOD of 21.8 mg/L resulted in *E. coli* concentrations equal or below 10 CFU/100 mL. The EU regulation on minimum requirements for water reuse states that the values of *E. coli* concentration need to be met in 90% or more of the samples and that none should exceed the maximum deviation of 1 log unit from the indicated value for each water class. This was not verified for any TOD tested for class A water. Since a TOD of 17.9 mg/L is sufficient to obtain a class B water, this is the suggested TOD to be applied at the plant. The presence of residual ozone was also evaluated, however the highest concentration measured was 0.16 mg/L. This is not a significant value, so it is expected that the immediate ozone demand was not met. A cost analysis would be necessary to understand the economic viability of the treatment, however this was not possible in the timeframe of this work due to lack of data.

This work also focused on the development of a risk assessment analysis that would allow the reuse of the treated water. For the risk assessment analysis, it was considered the irrigation of a park, identified as the main possible application for the reuse. A risk assessment analysis was conducted for public health and the environment. Regarding the public health risk, it was possible to determine the risk associated with each receptor and the global risk, after identifying the receptors, infection scenarios and barriers in use. A 1.77 risk level was obtained for adult users, 2.17 for maintenance workers, 2.37 for child users, leading to a global risk of 2.10, which, according to the APA, is negligible. For the environmental risk, the hydrographic region identified presents a classification of “Good” for the water quality and does not present a risk of nitrate pollution and eutrophication. Further information about the place of application would be necessary to assess the degree of infiltration in the aquifer or the run-off at the surface. In the scenario considered, without the use of barriers, a global risk for the environment of 3.89 was obtained for the concentrations of P and N, which presents an acceptable risk and 2.33 for *E. coli* concentration, which presents a negligible risk. The work developed can be used by the company as a model that can be easily adapted to other applications. Overall, the results obtained allow the use of the ozone treated water for park irrigation.

7 Work Evaluation

7.1 Goals Achieved

In this work, an ozonation treatment was studied with the objective of obtaining a treated residual water that meets the legislation established for its reuse. With this treatment it was possible to achieve a class B water. Another goal for this project was to study different applications for water reuse and develop a risk assessment and management strategy accordingly. It was possible to develop a risk assessment analysis for the application of the water for park irrigation that presented negligible risk for human health and acceptable risk for the environment. For other applications, this work can be used as a model, although some different considerations might be needed.

7.2 Final Consideration

It was possible to achieve the goals set at the beginning of this work. Due to time and resources limitations, it was not possible to obtain a higher amount of information about the ozonation system at different conditions, which would give more robust conclusions.

In the future, it would be advisable to conduct further tests at different TODs, namely the one suggested, to assure that the system can comply with the legislation for class B water in the long run. With further information given by the supplier, it would be helpful to conduct a cost analysis of the treatment to understand the economic viability of the project.

For the water reuse project, the following step should be the request of a license that allows the production and reuse of the treated water. Contacts must be made with the companies interested in this water to understand and discuss the conditions of application and the necessary level of treatment required. This work provides a solid example that is helpful for the request of the license, however further adjustments must be made according to the application stated in the license.

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Appendix A. Samples Collected

Table A1 represents the results of every sample obtained at an HRT of 2.0 min for every TOD tested.

Table A1 – Results of every sample obtained at an HRT of 2.0 min for every TOD tested.

Date	**HRT** (min)	**TOD** (mg/L)	**FC concentration**	**Log red. FC**	***E. coli* concentration**	**Log red *E. coli***
6/4	2.0	7.1	816400	0.33	82000	0.37
17/5	2.0	7.1	> 20000	-	11840	0.62
24/5	2.0	7.1	241960	-	13340	0.56
6/4	2.0	11.4	> 241960	-	48840	0.60
17/5	2.0	11.4	> 20050	-	2880	1.23
24/5	2.0	11.4	41060	-	3150	1.19
6/4	2.0	16.4	81640	1.33	9320	1.32
13/4	2.0	17.9	111	3.87	20	3.62
19/4	2.0	17.9	41	3.83	5	3.85
12/4	2.0	19.4	137	4.10	31	4.27
13/4	2.0	19.4	53	4.19	10	3.92
20/4	2.0	19.4	19	4.25	3	4.05
12/4	2.0	21.8	64	4.43	10	4.76
13/4	2.0	21.8	53	4.19	20	3.62
13/4	2.0	21.8	50	4.21	8	4.05
19/4	2.0	21.8	12	4.35	2	4.28
20/4	2.0	21.8	29	4.08	4	3.91
21/4	2.0	21.8	15	4.49	1	4.58
26/4	2.0	21.8	89	3.32	11	3.32
27/4	2.0	21.8	109	3.58	8	3.81

- Not determined, as the faecal coliforms concentration were over the detection limits of the method for the dilutions used.

FC – faecal coliforms; HRT – hydraulic residence time; TOD – transferred ozone dose.