Science of the Total Environment 851 (2022) 158329

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Sustainability assessment of wastewater reuse in a Portuguese military airbase

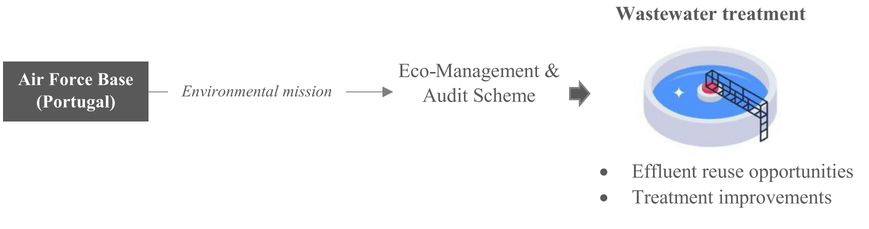
Joana Almeida [a,*], Abigail Monahan [b], Joana Dionísio [b], Filipe Delgado [c], Cátia Magro [b,*]

[a] *CENSE–Center for Environmental and Sustainability Research, Department of Environmental Sciences and Engineering, NOVA School of Science and Technology, NOVA University Lisbon, Portugal*
[b] *School for International Training, World Learning Inc., Brattleboro, VT 05302, USA*
[c] *Environmental Department, Portuguese Air Force, Portugal*

HIGHLIGHTS

- Wastewater treatments used at an Air Force Base in Portugal were reported.
- Wastewater reuse can add value to the environmental protection mission.
- Low nutrient removal due to the plant size and age and wastewater composition
- The treatment allows effluent reuse in aircrafts maintenance and cleaning activities.
- Chlorination may decrease the concentration of undesired compounds.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Frederic Coulon

Keywords:
Sustainability assessment
Wastewater
Water reuse
Air force
European Union EcoManagement and Audit Scheme

ABSTRACT

The current water-scarcity crisis that is being felt in Europe, namely in the southern region, has leveraged the development and implementation of national and regional water management plans. These policies aim to promote efficient wastewater reuse in industrial and urban sectors. Thus, stakeholders are now seeking strategies to enhance the sustainability of their wastewater treatment processes. The present work details the evaluation of the wastewater treatment methods used at an Air Force Base located in Portugal. In addition, this study also intended to determine how wastewater reuse can be implemented and add value to the environmental protection mission of the military airbase. Hence, an assessment of wastewater treatment practices was carried out, considering primary and secondary treatments. The chemical, physical, and biological indicators of samples collected over two consecutive years were analyzed to determine trends and fluctuations. The results revealed that the overall effectiveness of nutrient removal is low due to the oversized nature of the treatment plant, the age of the facility, and the composition of the wastewater. The effluent produced meets standards for non-potable reuse and could be used on base for aircraft maintenance and the cleaning of facilities. Nonetheless, the effectiveness of the plant could be improved by implementing a more advanced tertiary wastewater treatment to decrease the concentration of undesired compounds (e.g., total nitrogen), enabling the reuse of water in a broader range of activities.

---

* Corresponding authors.
E-mail addresses: js.almeida@campus.fct.unl.pt (J. Almeida), catia.magro@sit.edu (C. Magro).

http://dx.doi.org/10.1016/j.scitotenv.2022.158329
Received 11 July 2022; Received in revised form 12 August 2022; Accepted 23 August 2022

1. Introduction

The United Nations stated that most Mediterranean countries will have less freshwater available in 2050, in relation to 1990 levels. In addition, a higher demand for water is foreseen due to the global population growth that is expected to surpass 9 billion by 2050 (United Nations, 2019).

Portugal was estimated that over the next 40 years, annual precipitation will decrease significantly, while temperature will increase. Mountain and coastal areas, namely the western coast of Portugal, are predicted to be the most affected by temperature increases and precipitation fluctuations (Lavrnić et al., 2017; Quinteiro et al., 2019). The intensification of severe weather conditions due to climate change, together with urban development, has been threating freshwater supplies, compromising water quality and availability (Rebelo et al., 2020).

The present water crises in Europe, namely in southern countries, has emphasized the need to ensure a sustainable management of water and sanitation for the population. Thus, the United Nations has accounted this matter at the Sustainable Development Goals, in target number 6 (clean water and sanitation) (United Nations, 2021). Treated wastewater is a valuable resource for bionetworks protection, freshwater depletion decrease, as well as to be reused for potable and non-potable purposes (Food and Agriculture Organization of the United Nations, 2022). Therefore, wastewater treatment plays a prominent role in avoiding the release of pollutants into streams, controlling nutrient levels, and diminishing bacteria levels that could adversely affect the surrounding ecosystems.

Food and agriculture organization (FAO) global information system reported that between 2018 and 2022, Portugal withdrew a total of 6 billion m^3 of water per year. The volume of municipal wastewater that was treated during the same period was 0.3 billion m^3 per year. However, the volume of treated municipal wastewater that was directly used was only 0.003 billion m^3 per year, which corresponds to around 1.1 % of total treated wastewater (Food and Agriculture Organization of the United Nations, 2022).

Wastewater treatment in Portugal is regulated by Directive 91/271/EEC (European Commission, 1991) and transposed into Portuguese legislation by Decree-Law 348/98 (Diário da República, 1998a). This legislation details total nitrogen and phosphorus levels for effluent discharged by urban wastewater treatment plants (WWTP) and stipulates that tertiary treatment should be used, when necessary, by the receiving environment or water resources (Diário da República, 1998a). Currently, the majority of wastewater generated in Portugal is subjected to a secondary treatment (76 %), followed by tertiary (15 %), and primary treatment (7 %), meaning that <1 % of wastewater is untreated (European Committee for Standardization, 2015). Bearing in mind those data and that presently 57.5 % of mainland Portugal experiences water deficit, currently only approximately 10 % of treated wastewater is reused (Lavrnić et al., 2017).

Europe has created several national and regional water management plans aiming to minimize the risk of water scarcity by promoting efficient water use and reuse in industrial and urban sectors (Força Aérea Portuguesa, 2020). These programs include the National Water Plan (PNA), the National Program for the Efficient Use of Water (UNEP), the Strategic Plan for Water Supply and Water Sanitation (PENSAAR), and the Operational Program for the Sustainability and Efficiency in the Use of Resources (PO SEUR) (Zamparutti, 2020).

National programs stand to have the largest impact on entities under their direct control, such as military and governmental organizations. For instance, the European Army conscientiousness on environmental issues is leveraging additional novel initiatives to address this paradigm, as the Smart Blue Water Camps (SBWC). The SBWC project aimed to evaluate the water resources management and infrastructure sustainability and to recommend technological interventions to improve water management at the European military camp level. The proposed indicator framework, accustomed for the military sector, foresees a fast understanding of water management conditions in the studied military camps, comparisons, and identification of improvement opportunities (Makropoulos et al., 2019).

In addition to regional and national water management plans, the European Commission developed the European Union EcoManagement and Audit Scheme (EMAS) certification as a method for organizations to complete an environmental audit using standards defined in ISO 14001 (European Committee for Standardization, 2015). The feedback of the audit allows to identify critical aspects and to prioritize actions to develop a strategic plan to continuously improve the environmental performance of facilities (Honkasalo, 1998).

Currently, there are 45 companies and/or organizations in Portugal within EMAS. The size of these entities can vary, ranging from small companies to larger organizations, such as the European Maritime Safety Agency (EMSA). From the total amount of organizations registered in EMAS, 60 % are considered large units. The sector that is most represented is the manufacturing industry (57 %), namely oriented to non-metallic mineral products. Other relevant sectors with organizations that have EMAS certifications include companies involved in the capture, treatment and distribution of water, electricity generation and distribution, and public administration and security (Agência Portuguesa do Ambiente, 2022).

Considering both environmental protection and sustainable development, Portugal's Air Force Base No. 5 has focused their efforts on earning the EMAS certification as a means of continuously improving their environmental systems. In 2016, Air Force Base No. 5 became the first unit of European Union Defense and European Economic Area to earn the EMAS distinction. To obtain this certification, Air Force Base No. 5 conducted an extensive audit of all activities with an environmental impact occurring on base, then developed a multi-axis strategic plan for the continued assessment and diminishment of environmental impacts of on-base activities (Rodrigues et al., 2021).

Herein, synergies between the various established activities and the environment are potentiated, including wastewater treatment. The sustainable initiatives put forth by the strategic plan that are included in Axis II seek to promote the reuse of treated wastewater with a goal of reusing 50 % of treated wastewater (Força Aérea Portuguesa, 2020). Water reuse has demonstrated promising results for decreasing water stress, while increasing available water resources and closing the loop between water supply and wastewater disposal (Gibbons, 2016). To guarantee the quality of treated effluents and the success of the treatment plant, it is necessary to create a tailored solution after meticulous examination, adapted to local requirements, available funds, and modern technologies (Leverenz and Asano, 2011).

The present work aims to evaluate the ongoing wastewater treatment methods employed at the Portuguese Air Force Base No. 5 and determine feasible improvements to enhance the sustainability of the treatment process, to meet EMAS goals. Hence, all collected influent and effluent data from chemical, physical, and biological indicator testing was analyzed and compared with the allowed effluent discharge conditions outlined in Air Force Base No. 5's wastewater treatment plant license. Building up upon this analysis, current challenges and shortcomings of the existing wastewater treatment method were identified, as well as a screening of the most feasible techniques to improve the tertiary treatment. In addition, potential purposes for the reuse of treated effluent to accomplish the goals outlined in Axis II of the Air Force's Strategic Plan were assessed.

2. Methods

2.1. Case study description

The Monte Real Air Base, designated as Air Force Base No. 5, is a Portuguese Air Force Military airbase located in Monte Real, Leiria, Portugal (Fig. 1). The mission of this center is to guarantee the readiness of the Air Units and the logistical-administrative support, as well as internal security and immediate defense (Quality and Environmental Office - Air Force Base No. 5, 2021).

Air Force Base No. 5's secondary decentralized WWTP, with the capacity to serve 3000 people, opened in 1998 and is located on the airbase. The 3000-person capacity is equivalent to 530 m^3 of wastewater per day or 88.33 m^3 of wastewater per hour. The WWTP treats all the domestic and

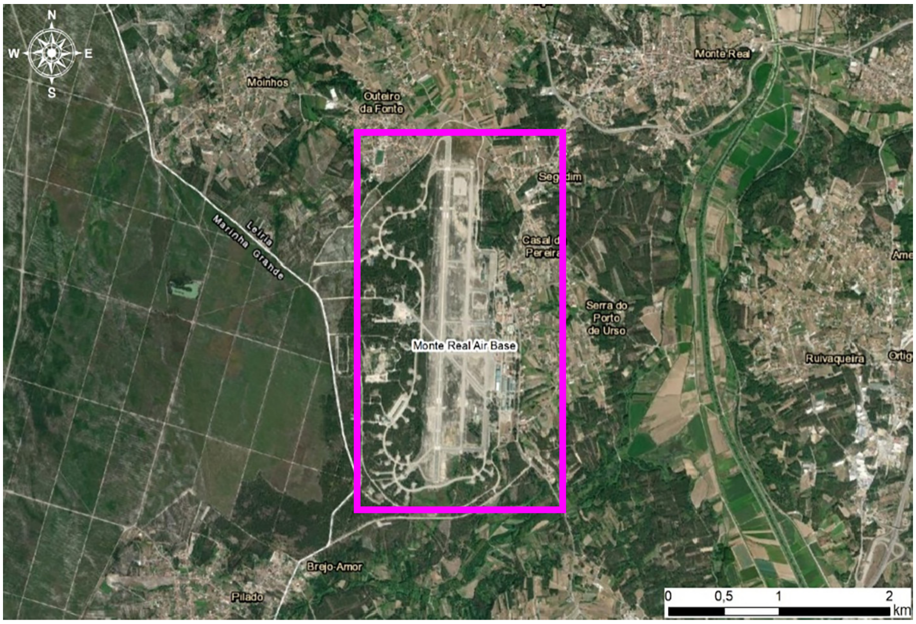


Fig. 1. Monte Real Air Force Base No. 5, Leiria, Portugal (source: Google maps).

industrial wastewater, as well as rainwater collected on site (Força Aérea Portuguesa, 2020).

There is a significant variation in the volume of wastewater treated due to population fluctuations and rainfall. This impacts the concentration of pollutants in the wastewater and the efficiency of the treatment. The WWTP is located at the lowest elevation in relation to the airbase, so gravity is the primary force used to transport wastewater to the treatment plant. Additionally, there are three electric pump stations to increase the efficiency of the transport process (Força Aérea Portuguesa, 2020). Fig. 2 depicts a diagram of the wastewater treatment process at the airbase.

The raw influent enters the WWTP through a channel equipped with an automatic grid remover that eradicates large solids, constituting the primary treatment process. The bypass channel is parallel to the main conduit and allows influent to move directly into the aeration tank when the main canal overflows and the floodgates are activated (Rocha, 2020). Upon entering the aeration tank, after passing through the main or bypass channel, the influent begins the secondary treatment process by mixing with oxygen and aerobic microorganisms to undergo biological treatment. During this step, the microbial community transforms dissolved pollutants and organic matter into biological flocs that are collected and removed as sediment. This treatment stage is contingent on microbial community growth, being imperative to optimize the conditions of the aeration tank. These parameters are achieved by automatic aerators controlled by an oxygen probe or timer which maintains a dissolved oxygen concentration of 2 mg/L. Dissolved oxygen concentrations below this limit favor the predominance of filamentous microorganisms which hinder sludge sedimentation (Brault et al., 2011).

An aerobic environment is maintained in the aeration tank. However, processes that require anaerobic conditions, namely denitrification and sludge digestion, take place simultaneously in the aeration tank. The anaerobic conditions are promoted by the aeration absence. Another factor affecting denitrification, and consequently, nitrogen values in the treated

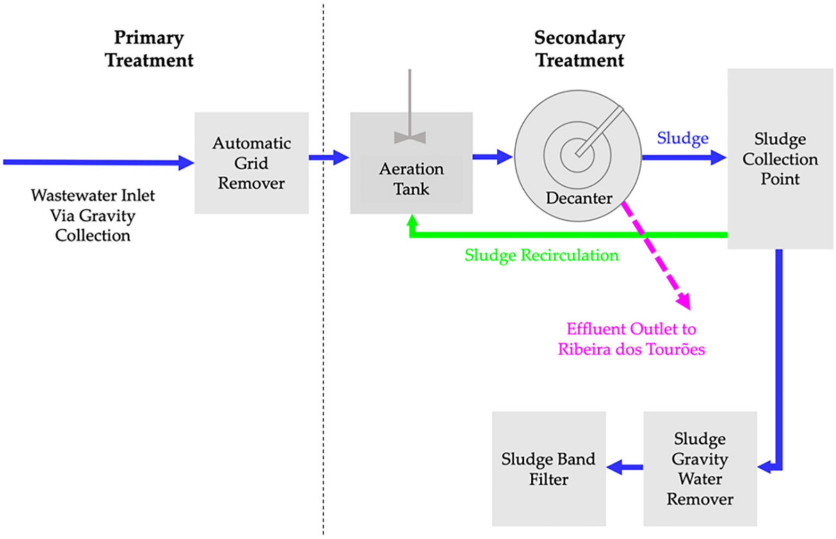


Fig. 2. Wastewater treatment plant scheme of Air Force Base No. 5.

wastewater is the difference between equivalent population of the project and current population being served. The aeration tank in tandem with the automatic grid remover aims to minimize the suspended solids amount and incorporate most of the organic matter into microorganisms and organic sediment. This is referred to activated sludge. Once the concentration of activated sludge exceeds optimal value, the sludge is purged, and the influent moves to the decanter (Lampinen et al., 2001).

In the decanter, activated sludge settles to the bottom of the tank and it is transported to the sludge collection point. Additionally, a bridge scraper moves sludge and scum from the surface of the water into a box that is connected to the sludge collection point. Although aerators are not included in the decanter, sludge is kept in aerobic conditions via purging to avoid the release of gas, which could result in settled sludge re-suspending in the partially treated influent. Additionally, residual oxygen dissolved in the partially treated influent is maintained to prevent denitrification of the sludge, which could also reduce the sludge's settling (Englande et al., 2015).

At the sludge collection point, sludge can be recirculated to the aeration tank if the concentration of microorganisms in the aeration tank is low, or it can be transported to a silo where gravity is used to remove the water from the sludge. Finally, the partially dried sludge is compressed in a band filter and lime is added to completely dehydrate the sludge; this treatment reduces the volume and disposal cost of the sludge, making it easier to transport (Al-Mutaz, 2004). The dried sludge (EWC 19 08 05) is collected in big bags that are disposed of or purchased by external companies to use as compost. After the sludge separation, effluent drains over the internal rim of the decanter to the effluent outlet, where it is discharged into the surrounding forest and eventually joins Ribeira dos Tourões (Força Aérea Portuguesa, 2019).

The effluent outlet is equipped with a flow meter, so the Base can determine the amount of effluent produced each year. The hydraulic retention time (HRT) of the wastewater is defined as the average length of time that a compound remains in treatment plant. The sludge collected at the airbase has an assessed HRT of 75 days, which is longer than the average range of between 15 and 30 days, due to the low organic load of the plant (Perry, 2020).

Wastewater treatment in Portugal is regulated by Directive 91/271/EEC (European Commission, 1991) and transposed into Portuguese legislation by Decree-Law 348/98 (Diário da República, 1998a). In 2016, the airbase obtained a five-year license to operate as a domestic WWTP. The license characterizes the treatment as secondary biological treatment by activated sludge in prolonged aeration. The discharge system is classified as "collected without protective work" indicating the effluent is discharged directly into the recipient medium, Ribeira dos Tourões. The license specifies the hydrographic region, basin, sub basin, and water biological oxygen demand (BOD_5), and classifies their ecological status as reasonable (Rocha, 2020). One of the general conditions of the license is that the Air Force Base No. 5 must pay an annual Water Resource Fee of €600 to be authorized by the Portuguese Environmental Agency to discharge wastewater. Moreover, general conditions state that the effluent cannot affect the quality of the receiving environment in a way that jeopardizes the resource or impacts its flow (Força Aérea Portuguesa, 2019). Finally, the license lists effluent discharge conditions and self-monitoring programs that must be implemented to ensure that conditions are met. Currently, chemical, physical, and biological parameters are regularly monitored to guarantee the effluent produced complies licensing standards (Força Aérea Portuguesa, 2020).

2.2. Influent and effluent indicators

Data on different chemical, physical, and biological indicators are collected periodically during the wastewater treatment process at the airbase. The collection points are as follows: (1) raw influent is collected before entering the treatment plant, (2) influent is collected from the aeration tank, (3) sludge is collected from the sludge collection point, (4) partially treated effluent is collected from the aeration tank and sludge recirculation point, and (5) treated effluent is collected from the effluent outlet. Once the airbase obtained a five-year license to operate as a domestic WWTP and EMAS certification in 2016, they began collecting and analyzing the data. Therefore, the period from 2016 and 2018 was selected to enable the analysis of trends in the WWTP indicators.

Table 1 summarizes the indicators analyzed at each collection point. Samples collected at points (1), (3), and (5) are analyzed by an external laboratory, Laboratório Tomaz, in accordance with method described in ISO 5667-10:1992 (ISO, 1992). Samples collected at points (2) and (4) are analyzed in the laboratory at the Air Force Base No. 5's WWTP.

A sample of raw influent was collected quarterly and analyzed at Laboratório Tomaz in 2018 to determine the composition of wastewater entering the WWTP. This enabled the WWTP operators to quantitatively compare influent and effluent, to determine the level of nutrient removal. The pH of the influent is determined to ensure it falls within the optimal range for microbial growth and the function of metabolic enzymes, to guarantee that wastewater can be efficiently treated in the aeration tank (Jin and Kirk, 2018). BOD_5 indicates the amount of oxygen the sample is consuming to degrade organic compounds without chemical assistance, where higher values mean excessive undesirable biological activity. Chemical oxygen demand (COD) measures the amount of oxygen needed to chemically oxidize organic compounds and inorganic compounds in a water sample (Perry, 2020). Total nitrogen and phosphorus represent the amount of nutrients in the solution. A sample is collected from the aeration tank four times per month to verify that the influent is receiving adequate treatment (Força Aérea Portuguesa, 2015).The sample collection volume was one liter of wastewater and was performed through a metal bar attached to a plastic container. In the WWTP laboratory, the pH, conductivity, dissolved oxygen (DO), and temperature of the sample are measured (Multi 3400i Handheld Multimeter, WTW, USA). If the DO concentration is above or below 2 mg/L, the aerators in the aeration tank are automatically adjusted as necessary to avoid filamentous microorganisms' formation (Brault et al., 2011).

Two sludge samples were analyzed in 2016. Sludge is collected from the aeration tank and tested at Laboratório Tomaz to evaluate pathogen concentrations in the sludge. *Escherichia coli* and *Salmonella* have been selected as the main indicators of pathogen levels. In addition, heavy metal levels are analyzed at this collection point. Sludge collected from the WWTP are submitted to a dehydration process and sold to AmbiPombal – Gestão de Resíduos, S.A (Pombal, Portugal) to collect/valorize or sell as compost or disposed of. Thus, it is critical to assess the concentration of pathogens or heavy metals in the sludge once it may pose health risk.

A one-liter liquid sample is collected from the aeration tank and sludge recirculation point. This sample is transferred into an Imhoff test cone to determine the settle solids (SS30) of the samples collected. After being transferred into the test cone, the sample is left for 30 min to allow solid sediments settle to the bottom of the cone and determine the volume of sediment at each collection point. The sludge must be in a range of 800–1000 mL/L and between 400 and 600 mL/L at the recirculation point and in the aeration tank, respectively. If there is not enough sediment in the aeration tank, the sludge at the recirculation point is recirculated instead of moving on to the gravity water remover (Força Aérea Portuguesa, 2015).

Treated effluent is collected and analyzed at Laboratório Tomaz monthly to verify that the effluent's biological, chemical, and physical indicators are within ranges specified on their discharge license. The pH of the effluent is analyzed to validate that the effluent is neutral, avoiding changes in the pH of the receiving environment. The biological and chemical oxygen demand are assessed to verify that the effluent's oxygen demand will not promote an anoxic environment in the receiving ecosystem (Donoso et al., 2018).

Total suspended solids (TSS) are analyzed to ensure that enough sediment has been removed and the turbidity of the effluent is proper for light to pass through the receiving environment. Nitrogen and phosphorus levels are assessed to verify that the effluent nutrient levels are below the limits, to protect the ecosystems against eutrophication scenarios. Hydrocarbon, oil, fat, phenol, and heavy metal levels allow the quantification of the extent of the treatment and the composition of the wastewater. The flow rate of treated effluent being discharged into the environment is

Table 1
Indicators analyzed in the sample collection points studied.

	Collection point				
	1. Raw Influent Analytical Control	**2. Aeration Tank Analysis**	**3. Sludge Analytical Control**	**4. Solid Sediments Record**	**5. Treated Effluent**
Indicator					**Analytical Control**
pH	■	■	■		■
O_2 (mg/L)		■			
Biological Oxygen Demand (mg/L O_2)	■				■
Chemical Oxygen Demand (mg/L O_2)					■
Total Nitrogen (mg/L N)	■		■		■
Nitric Nitrogen			■		
Ammonium (mg/kg)			■		
Total Phosphorus (mg/L)					■
Sulphides (mg/L)					■
Total Hydrocarbons (mg/L)					■
Oil and Fat (mg/L)					■
Phenols (mg/L)					■
Conductivity (µS/cm)		■			
Temperature (°C)		■			
E. Coli			■		
Salmonella spp.			■		
Organic Dry matter (%)			■		
Phosphorus, potassium, magnesium, calcium, cadmium, copper, nickel, lead, zinc, mercury, chromium (mg/kg)			■		
Iron, zinc and lead (mg/L)					■
Total Suspended Solids (mg/L)					■
Aeration Tank (mL/L)				■	
Recirculation point (mL/L)				■	

Note: The shaded cells correspond to the indicators analysed in each collection point.

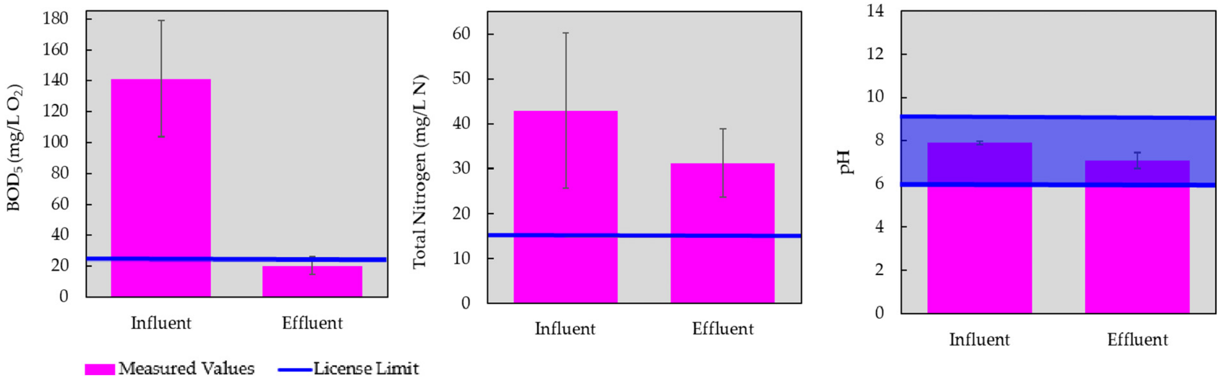


Fig. 3. Influent and effluent BOD$_5$, total nitrogen values and pH.

determined by a flow rate sensor on the effluent outlet pipe (Força Aérea Portuguesa, 2015).

2.3. Economics

Official documents from the airbase audit of on-base water consumption were evaluated to identify possible areas of non-potable water reuse and estimate the volume of water that could be reused for each identified non-potable purpose. The cost-benefit analysis of implementing water reuse at the proposed locations was calculated using the associated cost of using water provided by members of the Quality and Environment Office.

3. Results and discussion

3.1. Influent and effluent indicators

In 2018, Air Force Base No. 5 collected raw influent and treated effluent quarterly and determined its pH, BOD$_5$, and total nitrogen values. The average pH of raw influent and treated effluent samples collected were both within the acceptable license range between six and nine. Wastewater treatment resulted in a 10 % wastewater pH decrease. The treated effluent showed a pH closer to neutral than the raw influent.

The average BOD$_5$ of influent in 2018 was above the discharged conditions. Wastewater treatment decreased the BOD$_5$ of the wastewater by 86 %, resulting in an effluent with a BOD$_5$ value below the license limit. Initially, the total nitrogen level of the wastewater was around three times the license limit. Wastewater treatment decreased the nitrogen level by 27 %. However, the discharged effluent still had a nitrogen level about two times higher than the license limit. These results are reflected in Fig. 3.

All three data sets demonstrate that the indicator values decreased due to wastewater treatment. Nevertheless, the process resulted in only the BOD$_5$ indicator decreasing to meet the license limit. The pH level of the raw influent was already below the license limit, and neither the total nitrogen level before nor after treatment were below the license limit. Thus, Fig. 3 illustrates those nutrient levels, namely nitrogen, do not undergo a significant decrease because of wastewater treatment.

The primary reason for inefficient nitrogen removal is the WWTP is oversized. The facility is operating at 20 % of its intended capacity, and the predicted wastewater composition and organic matter volume does not correspond to the reality of the raw influent. The composition of the wastewater has a higher proportion of urine and lower levels of organic load than is intended for optimal treatment. This could be attributed to a significant portion of the base population living off base and not using the sanitary facilities as often as a larger population living on base would.

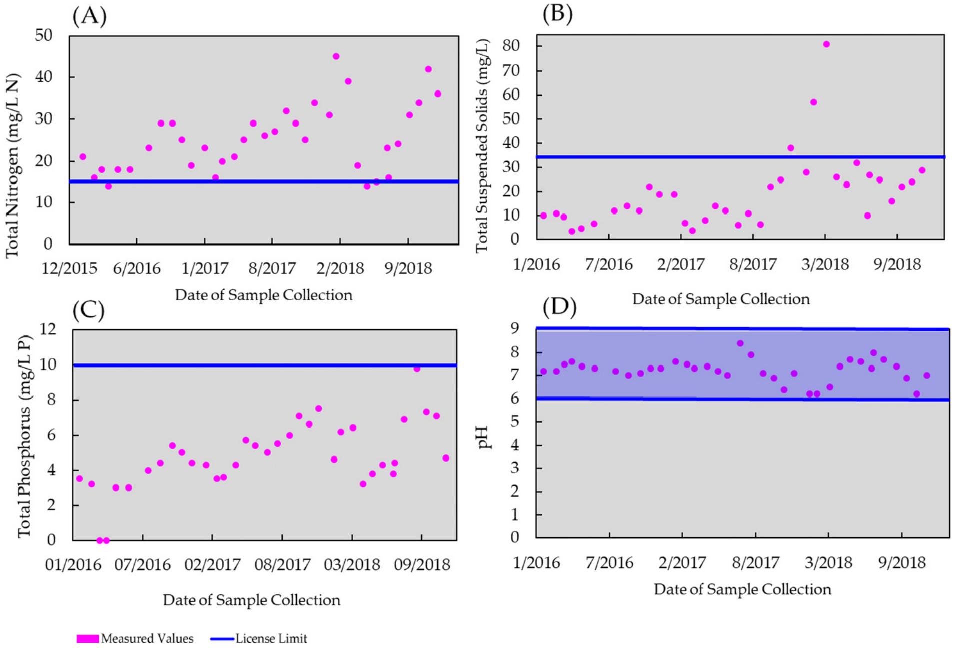


Fig. 4. (A) Total nitrogen, (B) total suspended solids, (C) total phosphorus, and (D) pH levels relative to license limits from 2016 to 2018.

Additionally, the low levels of organic load in the influent correspond to an average BOD_5 level in the lower 100 mg/L O_2 range. Domestic influent usually has a BOD_5 between 100 and 1000 mg/L O_2, where higher incoming BOD_5 levels are more favorable since macronutrients are removed relative to BOD_5 removal (Mara, 2013). Since 5 kg of nitrogen and 1 kg of phosphorus are eliminated for every 100 kg of BOD_5 removed, nitrogen removal is hindered by low initial BOD_5 levels. Another reason that inefficient nitrogen removal is observed is due to rainwater entry in the system that is related to gravity-fed nature of the treatment plant, further diluting the nutrients and decreasing the efficiency of the treatment (Quality and Environmental Office - Air Force Base N.o5, 2021).

It is important to note that according to Decree Law No. 236/98, it is not imperative for Air Force Base No. 5 to meet the nitrogen license limits because the WWTP is not located in a “sensitive area” as defined by the decree law (Diário da República, 1998b). However, there are environmental consequences associated with discharging effluent with high levels of nitrogen into the environment, including eutrophication. One way to promote denitrification without increasing organic load levels is to implement an anoxic tank as a primary treatment step to decrease the nitrogen levels of the influent before it enters the aeration tank. The lack of oxygen in this tank would force the bacteria to use nitrogen as an energy source, thus decreasing nitrogen levels (Perry, 2020). A denitrification primary treatment step would result in the total nitrogen levels of the treated effluent being closer, or meeting, the license limits.

To understand the trends of those data, pH, TSS, total nitrogen, and total phosphorus levels of the treated effluent were regularly collected between 2016 and 2018. When plotted (Fig. 4) The total nitrogen levels of the effluent samples trend upwards over time. Similarly, the total phosphorus levels of the effluent samples trend upwards over time. The total phosphorus levels of the collected samples all fall below the license limits. Total nitrogen is the only effluent indicator that was consistently higher than the license limit, although the TSS level exceeds license limits.

Most of the samples collected between 2016 and 2018 have TSS values below the license limit, although three samples had TSS levels above. Most samples had a total nitrogen level above the license limit, though there were four times where the total nitrogen level was less than the license limit. Relative to the acceptable range given in the license, the pH levels of the treated effluent have remained in the acceptable range from 2016 to 2018. The pH levels of the effluent samples have no clear trend over the three years, and no samples fell outside the license range. In summary, total suspended solids, total nitrogen, and total phosphorous levels all trended upwards over time.

The BOD_5 and COD of treated effluent samples were regularly measured. Between 2016 and 2018, BOD_5 and COD levels generally remained below the license limits. Nevertheless, some samples levels had exceeded these limits. As TSS, total nitrogen, and total phosphorous values presented in Fig. 4, BOD_5 and COD levels trended upwards toward the license limit. These results are displayed in Fig. 5.

Since BOD_5 correlates the amount of oxygen needed for the degradation of organic matter, and COD represents the amount of oxygen used to chemically oxidize the organic and inorganic matter, the ratio of BOD_5 to COD is a useful indicator to determine the effectiveness of biological treatment (Perry, 2020). A BOD_5 to COD ratio >0.5 indicates that the biodegradable fraction is high, and biological treatment has the potential to be successful. A BOD_5 to COD ratio between 0.5 and 0.3 suggests that the nonbiodegradable fraction is significant, so further testing should be conducted to assess if biological treatment has the potential to be effective. When the BOD_5 to COD ratio is lower than 0.3, biological treatment is unlikely to be successful. Analysis of the BOD_5 to COD ratio of effluent produced between 2016 and 2018 shows that most samples had a ratio <0.5, and a significant amount were <0.3, as depicted in Fig. 6.

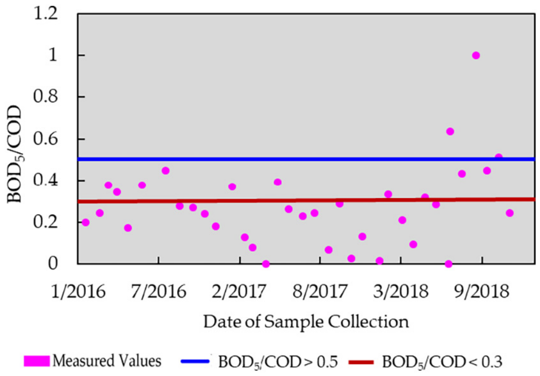


Fig. 6. BOD_5 to COD ratio for all samples collected between 2016 and 2018.

Analyzing the effluent indicator reveals that TSS, nitrogen, phosphorus, BOD_5, and COD values are trending upwards, suggesting that less nutrients are being removed by the treatment process over time. This could be attributed to the age of the treatment plant, as it has been operated since late 1990's, with minimal adaptations to the water quality variation and total population served decease over the years (Força Aérea Portuguesa, 2019). However, the effluent is being discharged to an area that is not affecting the surrounding ecosystems.

3.2. Action plan and economics

Table 2 summarizes moderate and significant water consumption activities on the Air Force Base No. 5 listed in the internal audit. The standards that the treated water would need to comply in different activities are listed according to Decree Law No. 119/2019 (Diário da República, 2019). The adequate treatment column refers to the primary, secondary, and tertiary designations.

It is not possible to use the treated effluent for several water consuming activities because the effluent does not meet the requirements provided in Decree Law No. 119/2019 (Diário da República, 2019), namely any type of potable reuse and instances of reuse that have high risk of dermal contact (e.g., washing personal protective equipment (PPE)). Effluent used for all activities, except for water used for washing aircrafts and cleaning facilities would require tertiary treatment.

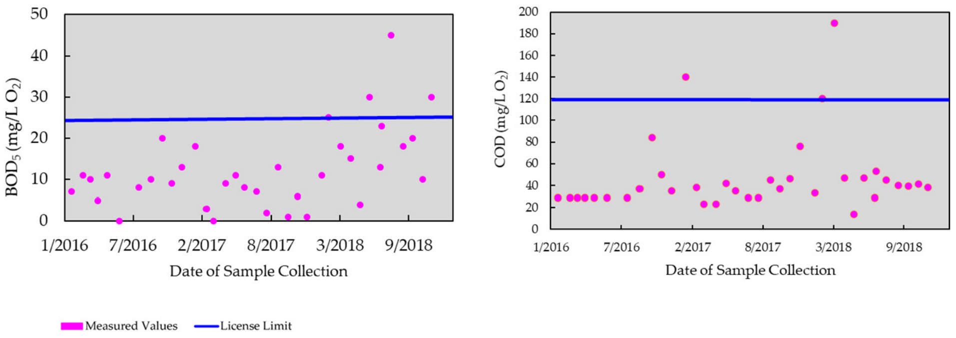


Fig. 5. BOD_5 and COD levels relative to license limits from 2016 to 2018.

Table 2
Water consuming activities and estimated reuse evaluation in the Air Force Base No. 5.

Water consuming activities	Reuse standards	Estimated annual reuse volume (m^3)[a]
Washing aircrafts	pH: 6–9 Turbidity: ≤5 *E. coli*: ≤10	50
Washing personal protective equipment	No standards outlined in DL119/19	0
Aircraft maintenance	No standards outlined in DL119/19	0
Maintenance of vehicles and equipment	No standards outlined in DL119/19	0
Laboratory work	No standards outlined in DL119/19	0
Cleaning of facilities, equipment, and vehicles	pH: 6–9 Turbidity: ≤5 *E. coli*: ≤10	100

[a] Volume estimated by the Quality and Environment Office.

The Air Force Base No. 5. WWTP has not received any significant intervention since it was built. Therefore, the top investment priority is to improve the wastewater treatment plant regarding maintenance and updates to enable that the effluent produced meets the nutrient limits outlined in the license. As a public institution, one of the barriers to implementing such recommendations is bureaucratic requirements and hieratical processes. Nevertheless, efforts are being made to ensure its continued ability to treat wastewater effectively. Thus, to draw a broad strategy to increase wastewater reuse in the activities that require tertiary treatment, drivers, and barriers of traditional and/or cutting-edge tertiary treatment methods applied to the case study were assessed (Table 3).

Ozonation, reverse osmosis, and electrochemical methods are costly and require the installation and maintenance of expensive and complex equipment. Thus, these treatment methods are not likely to be implemented due to budgetary constraints and the absence of personnel available. Nevertheless, electrochemical methods, such as electroremediation, might pose an alternative if initial investment is set in the implementation. Electroremediation when compared to other techniques, has demonstrated promising results, and consists of a low-level direct current application to promote physiochemical changes in wastewater pollutants (Magro et al., 2020). The effluent undergoes electrolysis at the electrodes, generating hydrogen and hydroxyl radicals, causing pollutants to undergo electromigration, electrophoresis, and electroosmosis. Organic contaminants' anodic oxidation occurs when the anode surface is directly encountered, or it is indirectly oxidated by oxidants formed in surrounding liquid media. In addition, hydrogen produced by the electrolysis of water can be collected and used as fuel for fuel cells, offsetting the energy costs associated with the tertiary treatment (Magro et al., 2021).

The disadvantages of implementing activated carbon also outweigh the advantages, making it an impractical tertiary treatment method. While

Table 3
Tertiary treatment methods' options and relevant drivers and barriers in the Air Force Base No.5 study case.

Treatment	Drivers	Barriers	References
Ozonation	• Greater efficiency than chlorine • 10–30-minute contact time • No chemicals or residues • Ozone production onsite • Treatment increases dissolved O_2 levels, avoiding the need for reaeration • Mitigation of taste and odor issues	• Complex equipment and system • Strong oxidizer makes the process more effective on effluents with low levels of TSS, BOD_5, and COD • High cost of treatment (due to electricity and infrastructure)	(Pistocchi et al., 2022; van Gijn et al., 2022; Walpen et al., 2022)
Ultraviolet (UV) radiation	• Effective disinfectant against pathogens including chlorine resistant pathogens • No chemicals or residues • Inexpensive and easy to use equipment • Not equipment intensive • 20–30 second contact time	• Low volumes of influent may be ineffective • Repairing and reversing the effects of treatment is possible in some organisms • High turbidity can harm the effectiveness of UV disinfection • Immediate success cannot be measured due to lack of residual disinfectant • Energy consuming	(Walpen et al., 2022; Y. Zhang et al., 2022)
Chlorination	• Chlorination is already used to treat water on the airbase • The residual disinfectant extends disinfection against recontamination • Cost-effective • Effective against a wide range of pathogenic organisms • Remove odors • Easy to adjust the quantity to accommodate influent volume changes	• Any concentration of chlorine is toxic to aquatic organisms • Dechlorination after treatment could be necessary • Complex microorganism are not exterminated by chlorine • Some chlorination by-products are hazardous with long-term effects	(Patton et al., 2022; W. Zhang et al., 2022)
Reverse osmosis	• No chemicals or residues • High-quality treated effluent • Easily added to existing WWTP infrastructure	• Costs associated with discharge of by-products (concentrate/-brine) • Effluent quality decreases over time due to membrane fouling • High operation and maintenance costs	(Im et al., 2022; Zhang et al., 2021)
Activated carbon	• No chemicals • Low cost and maintenance needs • Enhances effluent odor/taste • Efficient for filtering carbon-based chemicals and some microorganisms	• No efficiency in removing chemicals not attracted to carbon • Prone to clogging • Requires adequate contact with the filter • Can be ineffective or harbor some bacteria and viruses	(Pistocchi et al., 2022)
Constructed wetlands	• The base has available land • Low operation and maintenance costs • Provides habitat for wetland organisms	• Less consistent performance and longer hydraulic retention times in comparison to current techniques • Negatively impacted by changing environmental conditions and wastewater volumes • Toxic chemicals can hinder biological components	(Donoso et al., 2018; Mohamed et al., 2022)
Electrochemical methods	• Hydrogen production could be coupled • No chemicals • Stable under corrosive conditions • More efficient at higher contaminant concentration	• Relatively expensive implementation	(Almeida et al., 2021, 2020)

activated carbon is a low-cost and chemical-free tertiary treatment method, it is unable to filter out compounds with a low affinity for carbon and the activated carbon filter tends to harbor bacteria and viruses. Moreover, the activated carbon filter is prone to clogging, which would render the tertiary treatment system completely unusable for periods of time (Azam et al., 2022). Likewise, constructed wetlands are not well designed for the specific characteristics of this treatment plant; changing environmental conditions and population variations would result in less effective wastewater treatment (Zhou et al., 2022). Additionally, the wastewater treatment plant is already located at the edge of the Air Force Base No. 5 perimeter, so the large land requirement would pose an additional challenge.

Chlorination and UV radiation are both cost-effective tertiary treatment methods that require minimal equipment and maintenance and are effective against a wide range of pathogens, overcoming the two major barriers of cost and maintenance and infrastructure. UV radiation avoids the use of chemicals (Cerreta et al., 2020), although its implementation would require the purchase and installation of new UV light infrastructure and optimization research to ensure an effective dose is being administered. Furthermore, the overall energy consumption will increase with the implementation of this treatment, and the UV radiation will become less effective with the increase in TSS levels. Chlorination is effective for a wide range of pathogens, overcoming the major barriers of cost, maintenance, and infrastructure. Also, chlorine acts as a residual disinfectant that continues protecting treated effluent from recontamination. However, chlorination is not effective against all microorganisms (Wang et al., 2022) and there is potential for chlorine to form hazardous by-products, such as trihalomethanes (S. Zhang et al., 2022).

Overall, and namely due to financial reasons, chlorination stands out as a more advantageous tertiary treatment method. In fact, chlorine is already being applied on Air Force Base No. 5 for water treatment, and thus, there is the infrastructure and knowledge in place for implementing chlorine treatment. The associated risks of chlorine usage, namely hazardous by-product formation and toxicity to aquatic organisms could be rectified by using chlorine dioxide or peracetic acid as alternatives (Guo et al., 2022). Chlorine dioxide is not able to react with ammonia or aromatic organic compounds to produce trihalomethanes, decreasing the potential to form chlorinated organics. Peracetic acid is a mixture of hydrogen peroxide, acetic acid, and water that has similar oxidative properties to chlorine with minimal formation of by-products (Moharramzadeh et al., 2022). The successful use of chlorination will require identifying the minimum amount of chlorine that can be used to achieve the eradication of micropollutants and pathogens while minimizing risk to aquatic ecosystems. Additionally, it will be necessary to invest in effluent analysis using advanced analytical techniques, such as gas chromatography and high-performance liquid chromatography, to monitor hazardous by-product formation.

Additionally, long-term financial benefits of water reuse can offset the cost of implementing tertiary treatment. However, an accurate estimation of total costs related to the implementation of such technology hinges on region-specific costs. Herein, variable wastewater characteristics should be assessed to reach an accurate value (de Boer et al., 2022).

Table 4 shows all presently identified Air Force Base No. 5 activities where treated wastewater can be reused for non-potable uses. The financial benefit of implementing water reuse for these activities is calculated using the cost of energy consumption associated with pumping the water out of the wells and treating it with chlorine (associated cost comes to a total of €0.10/m^3). Reusing treated wastewater to fill toilet cisterns would require the installation of an infrastructure to separate treated wastewater from freshwater.

Table 4
Financial benefits incurred by water reuse.

Purpose for water reuse	Financial benefit (€/year)
Maintenance of green spaces	1000
Sanitary facilities (requires installation of infrastructure to transport effluent)	709
Cleaning of facilities, equipment, and vehicles	10
Firefighting training	10
Aircrafts wash	5

All activities, except for the cleaning of vehicles which can be driven down to the WWTP, require the transport of treated effluent to the location where it will be reused. This poses a challenge since installing piping and pumps to transport this water would significantly increase the cost that would hardly be offset by the financial benefit of implementing water reuse. Thus, an alternative solution to installing piping for water reuse that would enable all proposed water reuse activities, except for water reuse in sanitary facilities, is using firetrucks to transport water from the treatment plant to the final location. Implementing water reuse within the unit will support the Air Force Base No. 5 on achieving the goals outlined in Axis II of their strategic plan. In addition, this would contribute to accomplishing the guideline given in Decree Law No. 226-A/2007 (Procuradoria-Geral Distrital de Lisboa, 2007), that states that wastewater should be reused whenever possible for non-potable purposes. Following the above evaluation of how to improve the sustainability of Air Force Base No. 5 WWTP, some recommendations may be pinpointed, as follows:

1) Implement an anoxic chamber during primary treatment or a macrophyte pond (denitrification accelerator to decrease nitrogen concentration in the effluent)
2) Adopt tertiary treatment (e.g., chlorination)
3) Employ water reuse for the purposes listed in Table 2
4) Promote research and development activities and apply for external European Union funding for WWTP improvement.

Air Force Base No. 5 is continuously searching for solutions to overcome these issues and continue improving their services to serve the society and the environment. In this sense, further research should address feasible alternatives, with economic and environmental benefits.

4. Conclusions

Wastewater treatment plays an important role in reusing water resources and improving water quality, in line with the current water shortage and pollution. Effective wastewater treatment is critical to positive human-environment interactions.

The goal of the present research was to evaluate alternatives to improve the sustainability practices of Air Force Base No. 5's WWTP and provide an inventory of the plant efficiency on several indicators between 2016 and 2018.

The oversized nature of the WWTP and the composition of the wastewater, coupled with the treatment plant's age, is compromising the effectiveness of the nutrient's removal, which is decreasing over the years. The analysis of the samples from different collection points demonstrated that pH, BOD$_5$, and total nitrogen values decreased 10, 86 and 27 % respectively, after the treatment. However, the final effluent nitrogen concentration was 31.25 mg/L, corresponding to two times the license limit for this nutrient discharge. Furthermore, between 2016 and 2018, TSS, nitrogen, phosphorus, BOD$_5$, and COD values increased. Thus, the removal of nutrients generally decreases during the wastewater process.

Tertiary treatment would be environmentally beneficial since it may decrease reliance on freshwater extraction and decrease the discharge of micropollutants and pathogens into the environment, enhancing both the sustainability and effectiveness of treatment. The screening of the most common methods to apply at this treatment stage has highlighted the advantages of applying chlorination at Air Force Base No. 5. Effluent that has undergone tertiary treatment opens the door to several other potential areas for reuse at the airbase, which offers a financial incentive to implementing the treatment and to achieving the EMAS goals listed in Air Force Base No.5's Strategic Plan. Wastewater reuse would then be executed at the airbase to maintain green spaces, sanitary facilities and for cleaning and washing activities.

Employing more sustainable practices during wastewater treatment enables the decrease of the environmental impacts across several environmental aspects. Furthermore, other units could be encouraged to enhance the sustainability of their Air Force WWTP and be certificated by EMAS.

CRediT authorship contribution statement

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, J.A.,C.M. and A.M.; methodology, A.M.; software, J.A and A.M.; validation, C.M and F.D. and J.D.; formal analysis, J.A, A.M, C.M, F.D and J.D.; investigation, J.A and A.M.; resources, C.M.; data J.A, A.M and J.D, X.X.; writing—original draft preparation, J.A and C.M.; writing—review and editing, J.A, A.M, C.M, F.D and J.D.; visualization, J.A, A.M, C.M, F.D and J.D.; supervision, C.M and F.D.; project administration, C.M and J.D.; funding acquisition, C.M. All authors have read and agreed to the published version of the manuscript."

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by School for International Training, World Learning, Vermont, United States. The authors acknowledge the Portuguese Foundation for Science and Technology (FCT) for the support given to CENSE through the strategic project UIDB/04085/2020. The authors would also like to thank to the Air Force members, namely the Air Base No.5 Commander João Vicente and his team, for the availability to support this work.

References

Agência Portuguesa do Ambiente, 2022. I - Dados atualizados do EMAS em Portugal [WWW Document]. URL https://emas.apambiente.pt/graphs-emas?language=pt-pt. (Accessed 30 May 2022).

Almeida, J., Magro, C., Mateus, E.P., Ribeiro, A.B., 2020. Electrodialytic hydrogen production and critical raw materials recovery from secondary resources. Water 12, 1262 2020. 12, 1262 https://doi.org/10.3390/W12051262.

Almeida, J., Magro, C., Rosário, A.R., Mateus, E.P., Ribeiro, A.B., 2021. Electrodialytic treatment of secondary mining resources for raw materials extraction: reactor design assessment. Sci. Total Environ. 752, 141822. https://doi.org/10.1016/J.SCITOTENV.2020.141822.

Al-Mutaz, I., 2004. Design of RO Plants for Reclaiming of Treated Municipal Water Desalination and Water Treatment View Project.

Azam, K., Shezad, N., Shafiq, I., Akhter, P., Akhtar, F., Jamil, F., Shafique, S., Park, Y.-K., Hussain, M., 2022. A review on activated carbon modifications for the treatment of wastewater containing anionic dyes. Chemosphere 306, 135566. https://doi.org/10.1016/J.CHEMOSPHERE.2022.135566.

Brault, J.M., Whalen, P., Stuart, P., 2011. Early warning signs of bulking in an activated sludge system through interpretation of ATP data in a systems analysis context. doi:10.1080/09593330.2010.547874 32, 1649–1660. https://doi.org/10.1080/09593330.2010.547874.

Cerreta, G., Roccamante, M.A., Plaza-Bolaños, P., Oller, I., Aguera, A., Malato, S., Rizzo, L., 2020. Advanced treatment of urban wastewater by UV-C/free chlorine process: micro-pollutants removal and effect of UV-C radiation on trihalomethanes formation. Water Res. 169, 115220. https://doi.org/10.1016/J.WATRES.2019.115220.

de Boer, S., González-Rodríguez, J., Conde, J.J., Moreira, M.T., 2022. Benchmarking tertiary water treatments for the removal of micropollutants and pathogens based on operational and sustainability criteria. J. Water Process. Eng. 46, 102587. https://doi.org/10.1016/j.jwpe.2022.102587.

Diário da República, 1998a. Decreto-Lei n.º 348/98 de 9 de Novembro Portugal.

Diário da República, 1998b. Decreto-Lei n.º 236/98, de 1 de agosto Portugal.

Diário da República, 2019. Decreto-Lei n.º 119/2019, de 21 de agosto Portugal.

Donoso, N., Gobeyn, S., Villa-Cox, G., Boets, P., Meers, E., Goethals, P.L.M., 2018. Assessing the ecological relevance of organic discharge limits for constructed wetlands by means of a model-based analysis. Water 10. https://doi.org/10.3390/w10010063.

Englande, A.J., Krenkel, P., Shamas, J., 2015. Wastewater Treatment & Water Reclamation. Reference Module in Earth Systems and Environmental Sciences. Elsevier https://doi.org/10.1016/b978-0-12-409548-9.09508-7.

European Commission, 1991. Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC) (Belgium).

European Committee for Standardization, 2015. NP EN ISO 14001: 2015 - Sistemas de gestão ambiental. Requisitos e linhas de orientação para a sua utilização Brussels.

Food and Agriculture Organization of the United Nations, 2022. AQUASTAT Database [WWW Document]. URL https://www.fao.org/aquastat/statistics/query/results.html. (Accessed 26 May 2022).

Força Aérea Portuguesa, 2015. MBA5 340-3 Manual de Operação da Estação de Tratamento de Águas Residuais.

Força Aérea Portuguesa, 2019. Declaração Ambiental 2018 Base Aérea N.º5 Lisboa.

Força Aérea Portuguesa, 2020. Plano Estratégico de Sustentabilidade Ambiental da Base Aérea N.º 5 (PESA BA5) Portugal.

Gibbons, J., 2016. Kernels, in a nutshell. J. Log. Algebr. Methods Program. 85, 921–930. https://doi.org/10.1016/j.jlamp.2015.10.006.

Guo, Y., Xu, J., Bai, X., Lin, Y., Zhou, W., Li, J., 2022. Free chlorine formation in the process of the chlorine dioxide oxidation of aliphatic amines. Water Res. 217, 118399. https://doi.org/10.1016/J.WATRES.2022.118399.

Honkasalo, A., 1998. The EMAS scheme: a management tool and instrument of environmental policy. J. Clean. Prod. 6, 119–128. https://doi.org/10.1016/S0959-6526(97)00068-1.

Im, S.J., Kim, M.C., Jeong, G., Choi, H., Shin, J., Jang, A., 2022. Possibility assessment of ultrafiltration membrane pre-treatment efficiency for brackish water reverse osmosis-based wastewater reuse: lab and demonstration. Chemosphere 303, 134897. https://doi.org/10.1016/J.CHEMOSPHERE.2022.134897.

ISO, 1992. 5667-10:1992 - Water Quality - Sampling - Part 10: Guidance on Sampling of Waste Waters.

Jin, Q., Kirk, M.F., 2018. pH as a primary control in environmental microbiology: 1. Thermodynamic perspective. Front. Environ. Sci., 6 https://doi.org/10.3389/fenvs.2018.00021.

Lampinen, M., Assad, M.E.H., Curd, E.F., 2001. Physical fundamentals. Industrial Ventilation Design Guidebook. Elsevier, pp. 41–171 https://doi.org/10.1016/b978-012289676-7/50007-2.

Lavrnić, S., Zapater-Pereyra, M., Mancini, M.L., 2017. Water scarcity and wastewater reuse standards in Southern Europe: focus on agriculture. Water Air Soil Pollut. 228, 1–12. https://doi.org/10.1007/S11270-017-3425-2 2017 228:7.

Leverenz, H.L., Asano, T., 2011. Wastewater Reclamation and Reuse System.

Magro, C., Mateus, E.P., Paz-Garcia, J.M., Ribeiro, A.B., 2020. Emerging organic contaminants in wastewater: understanding electrochemical reactors for triclosan and its by-products degradation. Chemosphere 247, 125758. https://doi.org/10.1016/J.CHEMOSPHERE.2019.125758.

Magro, C., Almeida, J., Paz-Garcia, J.M., Mateus, E.P., Ribeiro, A.B., 2021. Hydrogen recovery in electrodialytic-based technologies applied to environmental contaminated matrices. Electrokinetic Remediation for Environmental Security and Sustainability, pp. 251–270 https://doi.org/10.1002/9781119670186.CH11.

Makropoulos, C., Koutiva, I., Kossieris, P., Rozos, E., 2019. Water management in the military: the SmartBlue Camp Profiling Tool. Sci. Total Environ. 651, 493–505. https://doi.org/10.1016/j.scitotenv.2018.09.056.

Mara, D., 2013. Domestic wastewater treatment in developing countries. Domestic Wastewater Treatment in Developing Countries, pp. 1–293 https://doi.org/10.4324/9781849771023.

Mohamed, A.Y.A., Siggins, A., Healy, M.G., Ó hUallacháin, D., Fenton, O., Tuohy, P., 2022. A novel hybrid coagulation-constructed wetland system for the treatment of dairy wastewater. Sci. Total Environ. 847, 157567. https://doi.org/10.1016/J.SCITOTENV.2022.157567.

Moharramzadeh, S., Ong, S.K., Alleman, J., Cetin, K.S., 2022. Stabilization and concentration of nitrogen in synthetic urine with peracetic acid and progressive freeze concentration. J. Environ. Chem. Eng. 10, 107768. https://doi.org/10.1016/J.JECE.2022.107768.

Patton, S.D., Dodd, M.C., Liu, H., 2022. Degradation of 1,4-dioxane by reactive species generated during breakpoint chlorination: proposed mechanisms and implications for water treatment and reuse. J. Hazard. Mater. Lett. 3, 100054. https://doi.org/10.1016/J.HAZL.2022.100054.

Perry, T.A., 2020. Avaliação da Remoção de Azoto por Nitrificação e Desnitrificação Simultânea Caso de Estudo: ETAR da Base Aérea nº5. NOVA School of Science and Technology, NOVA University Lisbon, Lisbon.

Pistocchi, A., Alygizakis, N.A., Brack, W., Boxall, A., Cousins, I.T., Drewes, J.E., Finckh, S., Gallé, T., Launay, M.A., McLachlan, M.S., Petrovic, M., Schulze, T., Slobodnik, J., Ternes, T., van Wezel, A., Verlicchi, P., Whalley, C., 2022. European scale assessment of the potential of ozonation and activated carbon treatment to reduce micropollutant emissions with wastewater. Sci. Total Environ. 848, 157124. https://doi.org/10.1016/J.SCITOTENV.2022.157124.

Procuradoria-Geral Distrital de Lisboa, M.P., 2007. DL n.º 226-A/2007, de 31 de Maio.

Quality and Environmental Office - Air Force Base N.o5, 2021. Relatório de Sustentabilidade Ambiental 2021 Monte Real.

Quinteiro, P., Rafael, S., Vicente, B., Marta-Almeida, M., Rocha, A., Arroja, L., Dias, A.C., 2019. Mapping green water scarcity under climate change: a case study of Portugal. Sci. Total Environ. 696, 134024. https://doi.org/10.1016/J.SCITOTENV.2019.134024.

Rebelo, A., Quadrado, M., Franco, A., Lacasta, N., Machado, P., 2020. Water reuse in Portugal: new legislation trends to support the definition of water quality standards based on risk characterization. Water Cycle 1, 41–53. https://doi.org/10.1016/J.WATCYC.2020.05.006.

Rocha, B., 2020. Valorização de efluentes urbanos. Caso de estudo base aérea N.º5, Monte Real. NOVA School of Science and Technology. NOVA University Lisbon, Lisbon.

Rodrigues, S., Inácio, A., Porença, M., Chainho, L., Vieira, S., 2021. Relatório do Estado do Ambiente 2020/21 Lisbon.

United Nations, 2019. World Population Prospects 2019 (ST/ESA/SER.A/423), United Nations. World Population Prospects 2019 (ST/ESA/SER.A/423) United Nations Department of Economic and Social Affairs; New York, NY, USA: 2019 New York, USA.

United Nations, 2021. The Sustainable Development Goals Report 2021 United States of America.

van Gijn, K., Zhao, Y., Balasubramaniam, A., de Wilt, H.A., Carlucci, L., Langenhoff, A.A.M., Rijnaarts, H.H.M., 2022. The effect of organic matter fractions on micropollutant ozonation in wastewater effluents. Water Res. 222, 118933. https://doi.org/10.1016/J.WATRES.2022.118933.

Walpen, N., Joss, A., von Gunten, U., 2022. Application of UV absorbance and electron-donating capacity as surrogates for micropollutant abatement during full-scale ozonation of secondary-treated wastewater. Water Res. 209, 117858. https://doi.org/10.1016/J.WATRES.2021.117858.

Wang, Z., Li, M., Liao, Y., Pan, Y., Shuang, C., Li, J., Zhou, Q., Li, A., 2022. Formation of disinfection byproducts from chlorinated soluble microbial products: effect of carbon sources in wastewater denitrification processes. Chem. Eng. J. 432, 134237. https://doi.org/10.1016/J.CEJ.2021.134237.

Zamparutti, T., 2020. Commission for the Environment, Climate Change and Energy Integrated Water Management and Policy Coherence in Regions and Cities ENVE. Brussels https://doi.org/10.2863/389869.

Zhang, S., Lin, Y.-L., Zhang, T.-Y., Hu, C.-Y., Liu, Z., Dong, Z.-Y., Xu, M.-Y., Xu, B., 2022b. Insight into the formation of iodinated trihalomethanes during chlorination, monochloramination, and dichloramination of iodide-containing water. J. Environ. Sci. https://doi.org/10.1016/J.JES.2022.05.011.

Zhang, W., Dong, T., Ai, J., Fu, Q., Zhang, N., He, H., Wang, Q., Wang, D., 2022a. Mechanistic insights into the generation and control of Cl-DBPs during wastewater sludge chlorination disinfection process. Environ. Int. 167, 107389. https://doi.org/10.1016/J.ENVINT.2022.107389.

Zhang, Y., Zhao, Y.G., Maqbool, F., Hu, Y., 2022c. Removal of antibiotics pollutants in wastewater by UV-based advanced oxidation processes: influence of water matrix components, processes optimization and application: a review. J. Water Process. Eng. 45, 102496. https://doi.org/10.1016/J.JWPE.2021.102496.

Zhang, Z., Wu, Y., Luo, L., Li, G., Li, Y., Hu, H., 2021. Application of disk tube reverse osmosis in wastewater treatment: a review. Sci. Total Environ. 792, 148291. https://doi.org/10.1016/J.SCITOTENV.2021.148291.

Zhou, T., Liu, J., Lie, Z., Lai, D.Y.F., 2022. Effects of applying different carbon substrates on nutrient removal and greenhouse gas emissions by constructed wetlands treating carbon-depleted hydroponic wastewater. Bioresour. Technol. 357, 127312. https://doi.org/10.1016/J.BIORTECH.2022.127312.