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Standing Technical Committee on Water (CW)

ENGINEERING, WATER AND FOOD NEXUS

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Editors

Armando Silva Afonso
Vice-Chair of WFEO Committee on Water
Order of Engineers of Portugal - OEP

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ENGENHEIROS

José Manuel Gonçalves
Order of Engineers of Portugal - OEP

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Standing Technical Committee on Water (CW)
World Federation of Engineering Organizations (WFEO)
Chair: Ignacio González-Castelão Martínez-Peñuela

INSTITUTO DE LA INGENIERIA
DE ESPAÑA

AUTHORS AND CONTRIBUTORS OF THE CHAPTERS

Chapter	Chapter Coordinator	Other Authors
1. Introduction	**Armando Silva Afonso** (World Federation of Engineers Organizations and Order of Engineers of Portugal) **José Manuel Gonçalves** (Order of Engineers of Portugal)	
2. Climate Change and food security	**Rogério Bonifácio** (Geospatial and Remote Sensing Unit at World Food Program – WFP, Rome, Italy)	**Valentin Pesendorfer** (Lead Data Engineer - Geospatial and Remote Sensing Unit at WFP, Italy) **Lorenzo Bosi** (World Food Program – WFP, Rome, Italy) **Muhamad Fajrin** (World Food Program – WFP, Rome, Italy)
3. Irrigation engineering and food production	**António Canatário Duarte** (Polytechnic University of Castelo Branco, Portugal)	**S. Lovelli** (University of Basilicata, Italy) **A. Melián-Navarro** (University of Miguel Hernández, Spain) **D. Castronuovo** (University of Salerno, Italy) **J. M. Gonçalves** (Polytechnic University of Coimbra, Portugal)
3.a. Case Study: Water Reuse in Citrus Farming - Carbon Emissions Reduction and Ecosystems Protection	**Manuela Moreira da Silva** (University of Algarve, Centre for Marine and Environmental Research CIMA ARNET and Centre of Engineering and Development - CEiiA, Portugal)	Flávia Resende (University of Algarve, Portugal) Jaime Aníbal (University of Algarve and CIMA-ARNET, Portugal) António Martins (Águas do Algarve, S.A., Portugal) Amílcar Duarte (University of Algarve and Mediterranean Institute for Agriculture Environment and Development - MED, Portugal)

Chapter	Chapter Coordinator	Other Authors
3.b. Case Study: Management of public irrigation systems in Morocco: Challenges and innovations for resilient agriculture	**Ayoub Guemouria** (International Water Research Institute, Mohammed VI Polytechnic University, Morocco)	**Rajaa Tanji** (Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts, Morocco) **Wafae El-Harraki** (National Superior School of Mines of Rabat, Morocco) **Ismail Elhassnaoui** (Edinburgh Napier University, UK) **Abdelghani Chehbouni** (Mohammed VI Polytechnic University, Morocco, and Centre d'Études Spatiales de la Biosphère, France) **Lhoussaine Bouchaou** (International Water Research Institute, Mohammed VI Polytechnic University, Morocco and Laboratory of Applied Geology and Geo-Environment, Faculty of Science, Ibn Zohr University, Morocco) **Chrysoula Pantsi** (Edinburgh Napier University, UK) **Lina Khaddour** (Edinburgh Napier University, UK)
4. Water and food industries	**Loraine Bainto-Ancheta** (University of the Philippines Los Baños, Philippines, Chiba University, Japan)	**Yukiharu Ogawa** (Chiba University, Japan)
5. Vulnerable groups	**C. Taguta** (University of KwaZulu-Natal, South Africa)	**T. Dirwai** (International Water Management Institute and University of KwaZulu-Natal South Africa) **L Nhamo** (University of KwaZulu-Natal and Water Research Commission, South Africa) **S. Mpandeli** (Water Research Commission, Tshwane University of Technology and University of Venda, South Africa) **A. Senzanje** (University of KwaZulu-Natal, South Africa) **T. Mabhaudhi** (London School of Hygiene and Tropical Medicine, UK, United Nations University Institute for Water, Environment and Health, Canada and University of KwaZulu-Natal South Africa)
6. Sustainability of water use systems	**Weiying Feng** (Beihang University, P. R. China)	
7. Final Remarks	**Armando Silva Afonso** (World Federation of Engineers Organizations and Order of Engineers of Portugal) **José Manuel Gonçalves** (Order of Engineers of Portugal)	

3.a. CASE STUDY: WATER REUSE IN CITRUS FARMING - CARBON EMISSIONS REDUCTION AND ECOSYSTEMS PROTECTION

Flávia C. Resende[1], Manuela Moreira da Silva[2] , Jaime Aníbal[3], António Martins[4], Amílcar Duarte[5]

[1] Chemical Engineer, MSc in Urban Water Cycle, Postgraduate in Project Management, Industrial Management and MBE in Environment. Over 21 years' experience in the environmental sector in consultancy, waste and wastewater management, water and soil laboratory analysis and water treatment projects in the steel, waste treatment, pulp, mining, process and service industries. Worked on optimizing processes and searching for new water sources in view of growing consumption and use needs. Development of water reuse projects. With a focus on solutions to the need to adapt to climate change.

[2] Graduated in Biology, MSc in Applied Ecology, and PhD in Environmental Sciences and Technology (University of Porto). Professor in Institute of Engineering, University of Algarve; Director of Master Program in Urban Water Cycle: Member of UNESCO Chair on Ecohydrology; Lecturer and Researcher with emphasis on: Water in Urban Areas. Sustainable Water Management, Ecohydrology; NBS and Carbon Sequestration in cities. Member of CIMA. Senior Researcher at CEiiA – Centre of Engineering and Development. Author of over 80 research publications and scientific communications.

[3] Graduated in Marine Biology and Fisheries and obtained his PhD in Ecology at University of Algarve (UAlg). He lectures Food and Sustainability related courses in several Graduation and Master Programs in the UAlg. His research deals with the effects of environmental changes on food quality, with emphasis on: seafood deterioration dynamics; valorization of seafood by-products; sustainable use of water for human activities. He is a member of CIMA-ARNET and author of over 40 research publications and 50 scientific communications.

[4] Graduated in Environmental Engineering (Aveiro University), a Master's degree in Sanitary Engineering (FCT-UNL) and a PhD in Environmental Biotechnology (Delft University of Technology). His professional activity is focused on sanitation projects, process control and O&M activities, Innovation and R&D projects and training programs in the water sector. He joined Águas do Algarve in 2004 as Process Engineer, and is currently Coordinator of the Innovation and Development Department and Director of the Operation and Maintenance of the Algarve Sanitation System.

[5] Graduated in Agronomy at Institute of Agronomy V.V. Dokutchaev of Kharkov, obtained a Master's degree in Citriculture at the Polytechnic University of Valencia and CIHEAM and a PhD in Agricultural Sciences/Fruticulture at the University of Algarve. He is currently director of the Agronomy degree programme, member of the General Council of the University of Algarve and author of over 130 technical and scientific publications in the field of fruticulture, with a special focus on citrus and sustainable agricultural practices.

1. Introduction

Anthropogenic factors and climate change are putting increasing pressure on natural water resources, threatening habitats and biodiversity (Libutti et al.2018, Rebelo et al., 2020). Worldwide, agriculture uses around 70% of the total water used in human activities. In addition, the demand for food and animal feed production tends to increase with the growth of the world population (Parris, 2010; Becerra-Castro et al., 2015; Chartzoulakis & Bertaki, 2015; Karandish & Šimunek, 2016). Meanwhile, freshwater use has exceeded recharge levels, leading to the desiccation of water streams, and the groundwater over-extraction has promoted saline intrusion phenomena in several coastal areas, posing additional constraints to agricultural irrigation, decreasing production and lowering crop yields (Jenkins & Sugden, 2006). To face this scenario, agriculture sustainability in more vulnerable regions, such as the south of Portugal, where water scarcity is a common reality, involves the choice of an alternative water supply and more efficient irrigation systems (Fatta-Kassinos et al., 2011; Jiang et al., 2016), as well as crop selection. To ensure the water demands of the human population are met without threatening the ecosystems, it is necessary to reduce the extraction of natural water and the discharge of treated effluents into the environment (Santana et al., 2019). The current technological advances in the wastewater treatment plants (WWTP) often allow the use of reclaimed water as a safe water source for different purposes, such as for the irrigation of some crops (Bixio et al., 2008; Garcia & Pargament, 2015; Nas et al., 2020). Nitrogen, phosphorus and potassium, present in treated effluents, can reduce the use of synthetic fertilizers (Becerra-Castro et al., 2015; Fatta-Kassinos et al., 2011; Adrover et al., 2012), contributing to the decrease in N_2O and CO2 emissions (Syakila et al., 2010; Chojnacka et al., 2019). However, water reuse may pose risks to public health and the environment, due to the possible existence of pathogenic microorganisms and toxic chemical compounds, such as disinfection products and emergent pollutants (Rebelo et al., 2020; Becerra-Castro et al., 2015; Fatta-Kassinos et al., 2011). In recent years, several European countries, including Cyprus, Greece, France, Italy, Spain, and Portugal, have been updating the legal framework (Portuguese Law 119/2019) for water reuse for multiple non-potable purposes, based on risk assessments. Thus, urban water reuse is considered as a safe process, provided that the treated effluents' risk framework management and the quality standards (based on physicochemical and microbiological parameters) are adequate for the proposed use (Rebelo et al., 2020; Becerra-Castro et al., 2015; EPA, 2012). For fruit trees, such as citrus trees, not in direct contact with irrigation water, the risks of transmission may be lower than for vegetables, which grow in direct contact with the soil and irrigation-reclaimed water (Becerra-Castro et al., 2015; Cirelli et al., 2012; Melloul et al., 2001). Citrus trees are native to Southeast Asia, but have been present in the Mediterranean basin for centuries and have become part of the Mediterranean diet, being used as fresh fruit, as well as in various dishes and desserts (Duarte et al., 2016). Located in southernmost area of Portugal, the Algarve region has a hot-summer Mediterranean climate, according to the Köppen climate classification, and presents a semi-arid coastal zone (Hugman et al., 2015; Estrela et al., 1996). Citrus fruits are the main Algarve crop, corresponding to a production of 368,000 t in 2020 (INE, 2022) of which 316,000 t were oranges. In general, agriculture accounts for 12% of the total greenhouse gas (GHG) emissions by human activities (IPCC, 2014), due to diverse field practices, including irrigation and fertilization. The sustainable management of these practices is considered to be the most promising mitigation pathway to reduce GHG emissions from agricultural soils [Liu et al., 2011; Scheer et al., 2012). In the Mediterranean, the use of drip-fertigation is increasing, particularly in high-value crops such as orchards (Brouwer et al., 19899, constituting an important practice for the efficient water and fertilizer use, and the reduction in production costs. Conversely, traditional irrigation and fertilization practices are responsible for N_2O emissions between 30% and 50% higher than fertigated crops (Kennedy et al., 2013; Shcherbak et al., 2014) due to the excessive application of nitrogen in traditional practices which led to higher nitrification rates (Shcherbak et al., 2014). However, agriculture has the potential to remove atmospheric carbon and orchards can function as carbon sinks, contributing to the mitigation of GHG emissions (Sahoo et al., 2021; West & Marland, 2002). Citrus orchards are considered to have a high carbon sequestration potential (Núñez-Florez et al., 2019), and the trees' ages were identified as a major determinant for the carbon potential sink capacity of such systems (Mo & Zang, 2012). This study assessed the feasibility of the use of treated urban effluent in citrus orchard irrigation as an alternative to groundwater and evaluated the respective environmental benefits.

2. Materials and Methods

This work was performed between March and July 2019 at the Algarve region, where agriculture is the biggest water user, and water scarcity is severe during most months of the year. The WWTP, which treated the effluent used in this study, is in Faro (37°01'04''N; 7°57'30''W), was built in 1989 and improved in 2009 to serve between 34,100 and 45,500 equivalent inhabitants, according to population fluctuations, mainly due to the seasonality of tourism.This WWTP is managed by the company responsible for the urban wastewater treatment, Águas do Algarve, S.A. (AdA)—Águas de Portugal Group, and is located inside the Ria Formosa Natural Park, a shallow coastal lagoon. The WWTP has a preliminary treatment with an automatic screening system, followed by removal of oil and grease by mechanical separation. There are two lines of biological secondary treatment by activated sludge process (ASP), each one consisting of an anoxic selector followed by an aerobic/anoxic reactor (carrousel type) and a circular decanter. The disinfection is carried out after secondary sedimentation with a UV system, and the treated effluent is discharged into a channel of the Ria Formosa. The discharge standards and the monitoring results of the treated effluent, reported by AdA, between January 2016 and November 2018 are presented in Table 1. Considering the existence of an orange (*Citrus sinensis*) orchard ('Valencia Late' grafted on 'Troyer' citrange) next to the WWTP, with 3397 trees in about 9.5 ha, we evaluated the feasibility of using the treated effluent for irrigation. This is an orchard with drip irrigation, with groundwater from the Campina-Faro aquifer. This aquifer is about 86.4 km^2 and presents a mean recharge of about 10 hm$_3$ year^{-1}, mostly by precipitation. The water of this aquifer often presents high concentrations of chlorides due to saline intrusion phenomena, and of nitrates resulting from intensive agricultural practices (Almeida et al., 2000; Nunes et al., 2006). The irrigation system presents two tubes along each row of trees, with dripper spacing of 0.75 m and 2 L.h^{-1} discharge rate. The application of synthetic fertilizers is by fertigation and during the experimental period pesticides were not applied.

Table 1: Characteristics of the treated effluent reported by AdA from Jan 2016 to Nov 2018.

Parameter	Limit Values Discharge Permit	Min-Max Average ± SD
Biochemic. Oxygen Demand, 20°C (mg L^{-1} O_2)	25	<5$^{(1)}$-11 <5$^{(1)}$
Chemical Oxygen Demand (g L^{-1} O_2)	125	18-110 34±11
Total Nitrogen (mg L^{-1} N)	Not Applicable	<3$^{(1)}$-34 11.3±7.8
Total Phosphorous (mg L^{-1} P)	Not Applicable	<0.50$^{(1)}$-5.3 1.4±0.9
Total Suspended Solids (mg L^{-1})	35	2-33 5±4
Faecal coliforms (MPN 100 mL^{-1})	100	3-260 103±75
Influent Flow Rate (m^3 day^{-1})	-	4585±996

(1) Limit of Quantification.

At the beginning of the experimental period, the chemical properties of the soil were characterized, dividing the orchard in three sectors (I–III in Figure 1) and collecting three samples, by sector, of the surface soil (0–10 cm) for further laboratory analysis. In the laboratory, the nine soil samples were air dried, ground on an agate mill and sieved over a 2 mm sieve. For each orchard sector, were quantified: texture of the fine earth material (<2 mm) was determined by Boyoucus method of densimetry (Day, 2015); organic matter (OM) by titrimetric by Walkley–Black method (Schumacher, 2002); total nitrogen (TN) by the Kjeldahl method (Bremner, 1960). The water extracts were obtained after the pre-treatment for wet analysis with distilled water. The pH and electric conductivity (EC) were quantified by electrometry, for pH using the Metrohm 780 pH meter in a 1:2.5 suspension of soil in water (ISO 10390:2021) and for EC using the WTWinolab level 2 with the TetraCon 325 in a 1:2 suspension of soil in water (EN 13038:1999). Chlorides (Cl-) were quantified by the titration Mohr method (Hesse, 2022) in a 1:5 suspension of soil in water. Phosphates (P_2O_5) were determined after Egner–Riehm extraction, by molecular absorption spectrometry (Baird et al., 2017). For boron (B), the azomethine-H spectrophotometric method (Sarkar et al., 2014) was used after extraction in Morgan’s solution (Sims, 2011). Calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) were extracted by the ammonium acetate method (Schollenberger & Simon, 1945), and for iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn), the Lakanen–Erviö extraction method (1971) was used. After extraction, metals were quantified by atomic absorption spectrometry (Baird et al., 2017), Ca, Fe, Mg, K, Na and Zn by flame, and Cu, Mn, and Mo by graphite furnace. The sodium adsorption ratio (SAR) was calculated. To assess whether there were significant differences ($p < 0.05$) in the soil characteristics between the different orchard sectors, a one-way ANOVA test was performed for a 95% confidence interval, using SPSS 26 (IBM, Armonk, NY, USA). After this, was used the Tukey test to check if there was any relationship between the sectors and the detected differences. The groundwater (GW) used for orchard irrigation, and the treated effluent (TE) were sampled monthly, between March and July 2019, and three replicates of each sample were collected for further analysis in the laboratory according to Table 2. We performed one-way ANOVA test for a 95% confidence interval, to assess whether there were significant differences ($p < 0.05$) over time for all parameters.

Table 2: Analytical methodology used to GW and TE characterization (Baird et al., 2017).

Parameter	Method	GW	TE
Ammonia (mg L^{-1} NH_4^+)	Molecular absorption spectrometry. SMEWW 4500-NH_3 F [41]	✓	✓
BOD5, 20oC (mg L^{-1} O_2)	Respirometric method. SMEWW 5210 D [41]	✗	✓
B (mg L^{-1})	Molecular absorption spectrometry. LAE -7.10.3 [46]	✓	✓
Ca, Fe, Li, Mg, K, Na (mg L^{-1})	Flame atomic absorption spectrometry	✓	✓
	SMEWW 3111 B	✓	✓
	[41]	✓	✓
Chlorides (mg L^{-1} Cl^-)	Argentometric method. SMEWW 4500 Cl^- B [41]	✓	✗
EC, 20 ºC (μS cm^{-1})	Electrometry. SMEWW 2510 B [41]	✓	✓
Phosphates (mg L^{-1} P)	Molecular absorption spectrometry, SMEWW 4500-P E [41]	✓	✓
Mn, Mo, Se, V (mg L^{-1})	Graphite furnace atomic absorption spectrometry SMEWW 3113 B [41]	✗	✓
Fluorides (mg L^{-1})	Electrometry. SMEWW 4500-F^- C [41]	✗	✓
Nitrates (mg L^{-1} NO_3^-)	Molecular absorption spectrometry, SMEWW 4500-NO_3 B [41]	✓	✓
Oxidability (mg L^{-1} O_2)	Titrometry. LAE - 9.1	✓	✗
pH (Sorenson scale)	Potentiometry, SMEWW 4500-H^+ B [41]	✓	✓
Sulphates (mg L^{-1} SO_4^{2-})	Molecular absorption spectrometry, LAE -7.50.2 [46]	✓	✓
Total Dissolved Solids (mg L^{-1})	Gravimetry. SMEWW 2540 C [41]	✓	✓
Total Suspended Solids (mg L^{-1})	Gravimetry. SMEWW 2540 B [41]	✓	✓
Turbidity (NTU)	Turbidimetry. ISO 7027:2019	✗	✓
Escherichia coli (CFU 100 mL^{-1})	Membrane filtration. [47]	✓	✓

During the wastewater treatment there are two types of greenhouse gas emissions (GHG) related to WWTP functioning, the direct and indirect emissions from all processes in the plant. Direct emissions refer mainly to N_2O, CH_4, and CO_2 emissions, usually generated by microbial metabolic activities during wastewater treatment and sludge treatment/disposal processes. Indirect carbon emissions result from the energy in operation and resources (Mo & Zang, 2012; Parravicini et al., 2022; Li et al., 2022). Previous studies, based on the data reported by EU Member States compliant with the Urban Wastewater Treatment Directive (UWWTD 91/271/EEC) made available by the European Environment Agency, estimated that direct N_2O emissions and indirect electricity emissions are the main contributors in the operation phase, followed by direct CH_4

emissions. Analyzing various scenarios to reduce emissions, it was demonstrated that the efficient use of electricity at the plant and the decarbonization of electricity would significantly help to improve the CO_2 e footprint of the WWTP [50]. Similar to most WWTP emission protocols, this study does not include the direct GHC emissions, as these GHG are emitted to the atmosphere through the natural process of decomposition anyway (Mo & Zang, 2012; Crawford et al., 2011). Attending to the specific energy consumption of Faro-Noroeste WWW(KWh/m^3), reported by AdA, we calculated the carbon emissions (CE) related to the treatment of the necessary volume of effluent for citrus irrigation, during the experimental period. To evaluate the impact of treated urban effluent reuse on the CE, we compared the CE related to both sources of water for citrus irrigation: (1) Considering the current irrigation dose during the experimental period, the energy consumption to groundwater extraction for irrigation was compared with the energy consumption for transporting the treated effluent from the WWTP to the orchard, assuming the same characteristics of the currently installed pump (submersible with a flow rate of 30 m^3 h^{-1} and 7.5 kW). Then, we calculated the CE related to both energy consumptions, considering the carbon emission factor for electricity in Portugal during 2019, 248.65 g CO2eq kWh-1 (EDP, 2020), including emissions of CO_2, CH_4, and N_2O; (2) Attending to the amount of synthetic N and P-fertilizers applied by fertigation during the experimental period (when groundwater was used for irrigation), and to the nutrient concentrations (N and P) in the treated effluent, we calculated the necessary adjustment of synthetic fertilizers, to ensure the same nutrient supply to the citrus trees. The CE related to the different amounts of synthetic fertilizers applied in both irrigation conditions was quantified using the CFP of N and P-fertilizers production in Europe at plant gate, calculated according to ISO 14067 [53] (N-fertilizer CFP = 1.14 kg CO_2e/kg and P-fertilizer CFP = 0.71 kg CO_2e/kg). The CE related to the transportation of fertilizers was not considered in these calculations.

3. Results and Discussion

The characteristics of the soil are presented in Table 3. The ANOVA test showed significant differences ($p < 0.05$) for all parameters. According to the Tukey test, for levels of pH, Phosphorus, Magnesium, organic matter, Iron, Manganese, Calcium and Molybdenum, sectors II and III do not present significant differences between them, but they present significant differences to sector I. The soil texture in sector I is sandy clay loam and in sectors II and III is loamy sand. As expected, clayey soil is richer in OM and, therefore, in P and N. Higher pH and higher Ca concentrations are associated with lower Fe bioavailability.

Table 3: Chemical soil properties (average standard deviation). Values with different letters (a, b and c) are significantly different at $p < 0.05$.

Parameter	Sector I	Sector II	Sector III	Mean Sectors I, II, III
pH	8.4a±0.1	7.6b±0.1	7.5b±0.1	7.8±0.5 *
EC, 20 ºC (dS m^{-1})	2.90a±0.06	1.99b±0.01	6.62c±0.04	3.84±2.12 *
TN (mg kg^{-1} N-NH$_4^+$)	624a±12	448b±36	520c±28	531±80 *
Cl- (mg kg^{-1})	676a±71	193b±183	534a±97	468±241 *
B (mg g^{-1})	0.60a±0.04	0.57b±0.03	0.67c±0.04	0.61±0.05 *
P$_2$O$_5$ (mg kg^{-1})	689a±71	403b±17	477b±17	523±134 *
OM (% m.m^{-1})	1.4a±0.1	1.2b±0.1	1.1b±0.1	1.2±0.2 *
Ca (mg kg^{-1})	560a±8	345b±18	382b±3	429±100 *
Fe (mg kg^{-1})	39.0a±1.4	78.3b±5.5	78.1b±1.9	65.1±19.8 *
Cu (mg kg^{-1})	14.1a±0.3	14.2a±0.6	19.1b±0.7	15.8±2.5 *
Mg (mg kg^{-1})	493a±2	247b±2	250b±2	330±122 *
K2O (mg kg^{-1})	1092a±7	932b±10	1261c±26	1095±143 *
Na (mg kg^{-1})	48.3a±2.9	14.2b±0.6	44.5a±1.1	35.7±16.3 *
Mn (mg kg^{-1})	30.6a±0.9	22.7b±1.5	23.9b±0.6	25.7±3.8 *
Mo (mg kg^{-1})	1.25a±0.02	2.10b±0.15	2.45b±0.02	1.93±0.54 *
Zn (mg kg^{-1})	13.8a±0.2	12.4b±0.4	14.4a±0.2	13.4±0.9 *

* There are significant differences at ANOVA test

Between March and July 2019, the local mean atmospheric temperature was 19.3 ^{o}C, with a minimum of 12.8 ºC (March) and a maximum of 32.0 ºC (June). The local precipitation was below 5 mm, and from June the percentage of water in the soil was less than 20% (IPMA, 2019).Between March and July 2019, the local mean atmospheric temperature was 19.3 C, with a minimum of 12.8 ºC (March) and a maximum of 32.0 ºC (June). The local precipitation was below 5 mm, and from June the percentage of water in the soil was less than 20% (IPMA, 2019). The total groundwater consumption for orchard irrigation during the experimental period was 27,891 m3. The water consumption per month increased from the coldest month (March) to the warmer months (June and July), according to Figure 1. This figure also shows the consumption in the same months of the previous two years, as well as the mean per month over the three years.

The results of groundwater monitoring during the experimental period, and maximum recommended values (MRV) in Portuguese legislation, are summarized in Table 4. In general, all parameters in groundwater showed lower values than MRV, except for electrical conductivity (1.45 ± 0.04 dS m^{-1}), chlorides (395 ± 138 mg L^{-1} Cl^{-}) and TDS (1044 ± 163 mg L^{-1}). These results seem to confirm the occurrence of saline intrusion phenomena in the Campina-Faro aquifer, as reported before, e.g., by Nunes et al. [36]. During the experimental period, there were significant differences ($p < 0.05$) for all parameters over time, confirming the seasonality effect, except for oxidability and sulphates. The oxidability values were very low (1.3 ± 0.7 mg L^{-1} O^2) over all months and sulphate concentrations remained stable throughout the experimental period (217 ± 18 mg L^{-1} SO_4^{2-}).

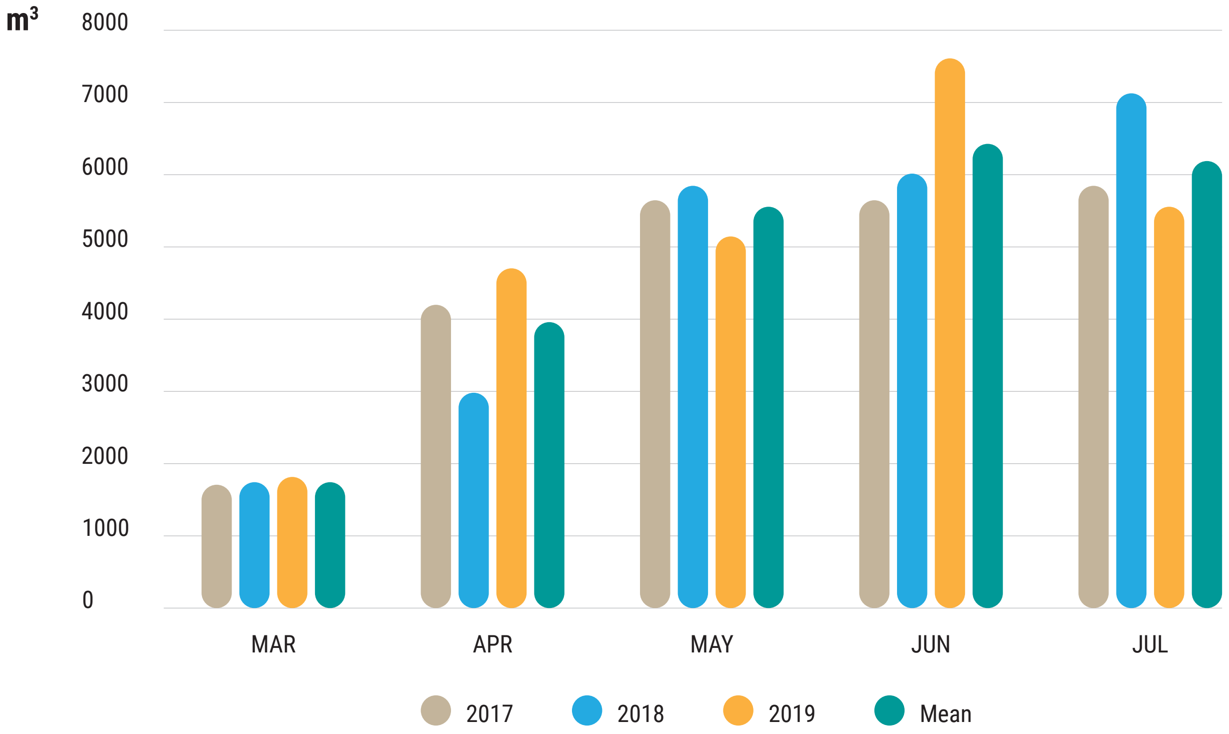

Figure 1: Evolution of groundwater consumption for orchard irrigation during the experimental period, similar months in 2017 and 2018, and mean per month.

Table 4: Chemical characterization of GW and TE throughout the experimental period experimental period (average ± standard deviation).

Parameter	Groundwater	Natural Water for Irrigation MRV (1)	Treated Effluent (TE)	Water Reuse QS(2)
Ammonia (mg L-1 NH_4^+)	0.023 ± 0.020	--	3.92 ± 1.59	10
BOD5, 20 ºC (mg L^{-1} O_2)	7	--	10.1 ± 5.3	≤25
B (mg L^{-1})	0.08 ± 0.02	0.3	0.16 ± 0.03	--
Ca (mg L^{-1})	52.5 ± 1.1	--	34.1 ± 1.1	--
Fe (mg L^{-1})	✗	5.0	0.44 ± 0.03	2.0
Li (mg L^{-1})	✗	2.5	0.11 ± 0.01	2.5
Mg (mg L^{-1})	51.2 ± 11.4	--	34.9 ± 7.0	--
K (mg L^{-1})	35.6 ± 19.4	--	23.4 ± 11.7	--
Na (mg L^{-1})	123 ± 6	--	142 ± 25	--
Chlorides (mg L^{-1} Cl^-)	395 ± 138	70	311 ± 94	--
EC, 20 ºC (dS m^{-1})	1.45 ± 0.04	1	1.29 ± 0.23	--
Phosphates (mg L^{-1} P)	<0.125(3)	--	0.5 ± 0.34	5 (Total Phosphorous)
Mn (mg L^{-1} Mn)	✗	0.20	0.02 ± 0.01	0.2
Mo (mg L^{-1})	✗	0.005	0.21 ± 0.15	0.01
Se (mg L^{-1})	✗	0.02	<0.01(3)	0.02
V (mg L^{-1})	✗	0.10	<0.01(3)	0.1
Fluorides (mg L^{-1})	✗	1.0	0.15 ± 0.02	2.0
Nitrates (mg L^{-1} NO_3^-)	<4(3)	50	4 ± 1	15 (Total Nitrogen)
Oxidability (mg L^{-1} O_2)	1.3 ± 0.7	--	✗	--
pH (Sorenson scale)	7.41 ± 0.17	6.5-8.4	7.87 ± 0.14	--
SAR	3.6 ± 0.8	8	4.1 ± 0.6	--
Sulphates (mg L^{-1} SO_42^-)	217 ± 18	575	171 ± 15	--
TDS (mg L^{-1})	1044 ± 163	640	830 ± 166	--
TSS (mg L^{-1})	1.0 ± 0.8	60	3.5 ± 1.8	≤35
Turbidity (NTU)	✗	--	7.5 ± 2.4	--
Escherichia coli (CFU/100 mL)	0 to 2	100	2 to 100	≤100

– not referred; X not quantified; (1) maximum recommended value in Portuguese Law 236/98, Annex XVI; (2) quality standards in Portuguese Law 119/2019 and EU Regulation 2020/741, for fruits not in direct contact with irrigation water [54]; (3) limit of quantification.

The overall volume of treated effluent produced by the WWTP, during the experimental period was about 619,359 m^3, 22 times higher than the volume of groundwater consumed for irrigation. The specific energy consumption on the WWTP during the experimental period was 0.77 $kWh.m^{-3}$, meaning that 118,583 kg CO_2e were emitted. Figure 2 presents the monthly variation on treated effluent production during the experimental period and in the same months of the previous two years, as well as the mean per month over the three years.

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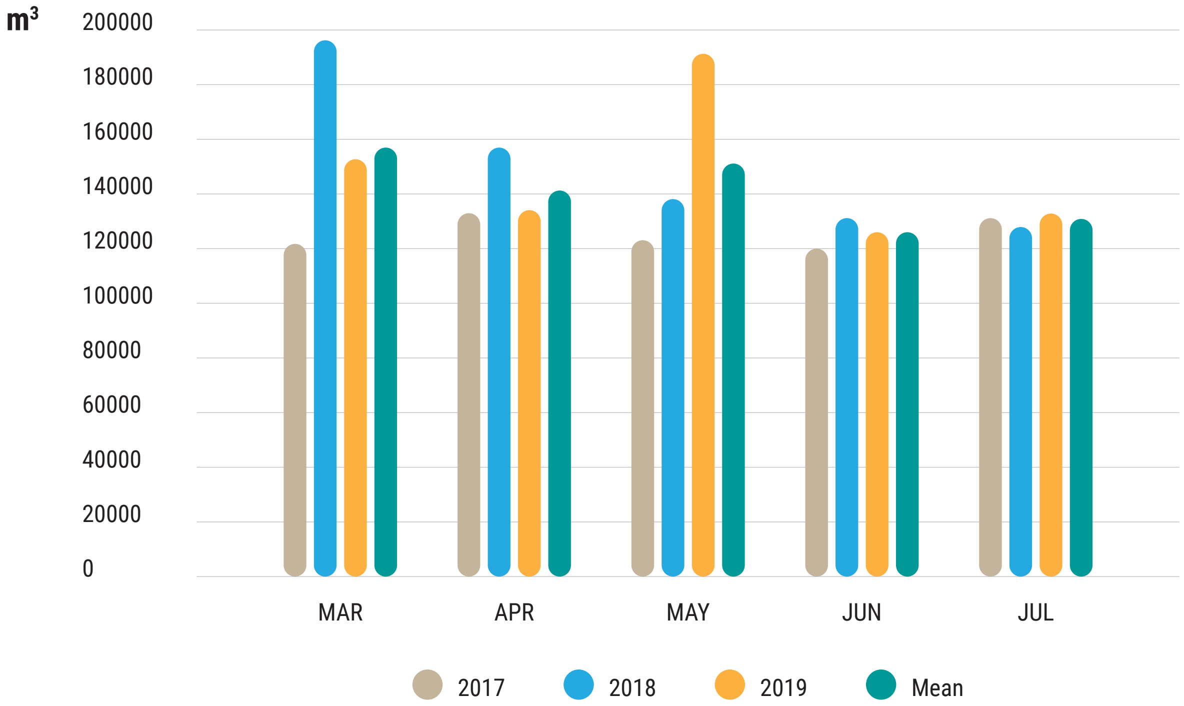

Figure 2: Evolution of treated effluent production during the experimental period, on similar months in 2017 and 2018, and mean per month.

Table 4 also shows the characteristics of the treated effluent and Quality Standards, for water reuse in fruit tree irrigation. All parameters meet the quality standards, except for molybdenum and total dissolved solids. Molybdenum can reach the wastewaters from diverse anthropogenic sources, such as metallurgical processing, coal and petroleum burning or discharges of phosphate detergents. Molybdenum is an essential micronutrient for plants, but toxic if present in high concentrations. The soil properties its availability, the molybdenum phytotoxicity being greater in alkaline soils, and in dicotyledonous species (McGrath et al., 2010). Despite this, under natural conditions there is no reference to the toxicity of molybdenum in citrus trees. The treated effluent presented a higher organic matter content than the groundwater (in TE: BOD = 10.1±5.3 mg L-1 O_2 and in GW: oxidability = 1.3±0.7 mg L^{-1} O_2), suggesting that the use of TE can have a positive effect on soil organic carbon and on its water retention (Becerra-Castro et al., 2020; Baldock & Sparks, 2003; Nelson, 2000). Attending to the ammonia (3.92±1.59 mg L^{-1} NH^{4+}), nitrate (4 2 mg L^{-1} NO^{3-} and phosphate (0.57±0.34 mg L^{-1} P) concentrations, it is expected that the discharge of the treated effluent into Ria Formosa may cause eutrophication phenomena. Alternatively, if this treated effluent is used for irrigation, then it contributes to increasing the N-forms and P-forms in the soil. Efficient irrigation and fertilization practices can be an important contribution to the ecosystem's sustainability and agriculture development (Li et al., 2020). These results confirmed that the use of the treated effluent for irrigation, with higher nutrient levels than groundwater (phosphorous and nitrogen), instead of being discharged into the Ria Formosa lagoon, can be used for supply, at least a part, of the crops requirements, as reported before in other studies (Becerra-Castro, et al., 2020). The quantified values for E. coli are compatible with the water reuse for the irrigation of fruit trees, and the risk of contamination is even lower when using a drip irrigation system which means that the irrigation water does not come into contact with the aerial part of the plant. Although in the Portuguese legal framework E. coli is proposed to be the "hazard" indicator as it is the most suitable indicator of fecal contamination, the water quality is not considered the only parameter that can ensure health protection in water reuse projects. The adoption of other preventive measures to reduce hazards and exposure to hazards must be identified, i.e., barriers to minimize contact with reclaimed water and recognized receptors. The irrigation type and schedule, harvest options, and crop characteristics can limit the contact between people and pathogens present in reclaimed water. Previous studies showed that drip irrigation of high-growing crops, 50 cm or more above the ground, allows a 4 log10 pathogen reduction meaning 2 equivalent barriers (Rebelo et al., 2020). These studies were carried out in a vineyard irrigated with reclaimed water from an urban WWTP, where grapes are used exclusively for wine production, therefore in conditions not very different from a citrus orchard. Regarding the conductivity of the irrigation water, it is recommended not to use water with an electrical conductivity greater than 3 dS.m^{-1}; the adjusted sodium adsorption ratio should be less than 9 and the chloride ion concentration less than 355 mg L^{-1}. It is also not recommended to use water with boron concentrations above 0.75 mg L^{-1}.

The production of oranges was 117.3 t (25 t ha^{-1}), which is considered a relatively low yield for a 30-year-old orchard, but consistent with the relatively small size of the trees. Orange production is considered to contribute to GHC mainly due to the CO_2 and CH_4 emissions on the production of synthetic fertilizers and to the N_2O emissions from soil denitrification during the agricultural practices (Ribal et al., 2009). In our work, we calculated the CE per kg of harvested oranges, considering the contribution of synthetic fertilizers production and the energy consumption in pumping water for irrigation, during the experimental period (Table 5).

Table 5: Carbon emissions related to the energy consumption in pumping water for irrigation and orchard fertilization.

Water source for irrigation	Energy consumption in water pumping (kW)	Synthetic fertilization		Carbon Emissions	
		N-fertilizer (Kg)	P-fertilizer (Kg)	kg CO_2e	g CO_2e / kg^{-1} of oranges
Groundwater	3449	870	733	858.968	7.32
Treated effluent	1734	76.7	683	431.662	3.68

Our results show that the wastewater reuse allows for a significant reduction in CE related to orange production, minus 50% for the water pumping for irrigation, minus 91% for the N-fertilizer and minus 7% for the P-fertilizer, which means minus 3.64 g CO^2e. kg^{-1} of harvested oranges and a reduction of 427.306 kg CO_2e per total orange production, during the experimental period. These results show that wastewater reuse in citrus orchards irrigation can contribute to more sustainable food production. Previous works (Mordini et al., 2009) presented the carbon footprint of oranges produced in Spain, Italy and Brazil, showing that the values vary considerably from

80 to 330 g CO_2e per kg of harvested oranges. In our work, the carbon emissions per kg of harvested oranges present lower values because we only quantified the CE directly related to the replacement of groundwater by the treated effluent in orchard irrigation. The N_2O emissions due to the agricultural practices, not considered in this study, will be relevant to the carbon footprint and similar in both irrigation conditions. Previous studies in eastern Spain (Núñez-Florez et al., 2019) reported that an adult citrus tree (over 12 years old) can fix a net carbon amount higher than 73.29 kg CO_2 tree^{-}1 yr^{-}1 and total biomass of the annual organs accounted for more than 70% of this value, specifically, harvested fruit. According to this reference, we estimated that during the five-month experimental period, the carbon sequestration in biomass was about 30.55 kg CO_2 tree^{-1}, representing about 103,747 kg CO_2 sequestered by the orchard of which 72,623 kg of CO_2 was converted into orange biomass. These results indicate that this orchard has sequestered 87.5% of the carbon emissions related to the energy consumption necessary for the urban wastewater treatment, highlighting its importance in reducing the WWTP impact on GHC emissions.

4. Conclusions

This study shows that treated effluent reuse is technologically feasible for citrus orchards irrigation and can contribute to improving the carbon fluxes, reducing GHC emissions, and promoting carbon sequestration. According to our results, the GHC emissions related to orange production can decrease, mainly due to the reduction in energy consumption of water pumping for irrigation, and the need to apply a smaller amount of synthetic fertilizers, since the treated effluent presents higher concentrations of nitrates and phosphates than groundwater. In addition, although further studies are needed, this alternative source of water for citrus irrigation presents other benefits for natural ecosystem protection.

The use of reclaimed water prevents the overexploitation of coastal aquifers, reducing saline intrusion and, at the same time, reducing nutrient discharges into the Ria Formosa, avoiding eutrophication phenomena in this coastal lagoon, classified as a Ramsar site. Since the organic matter content in the treated effluent is higher than in groundwater, it is expected that the use of reclaimed water promotes water retention in soil, improving plant growth and thus carbon sequestration. This improvement in the carbon sequestration by the citrus orchard will increase fruit production and the farmer profits. Finally, this work highlights the great potential of citrus orchards to sequester GHC emitted by the urban WWTP, and its potential contribution to the carbon neutrality of the urban wastewater treatment.

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