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Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigating olive trees

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A R T I C L E I N F O

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A B S T R A C T

Fertigation management of olive grove is highly complex, especially when reclaimed water is used for irrigation. Nitrogen (N) is the main nutrient component of olive trees which, traditionally, has led to an excessive use in fertilization programs. This problem can be exacerbated if reclaimed water is used since it already contains N. For this reason, water quality must be considered in the fertilization plan. Both total content and N form arriving to the trees have implications in olive tree nutrient requirements as well as the environment. If reclaimed water particularities and the length of the pipes of water distribution networks are considered, the form and total concentration of N can change over space and time. In this work, both spatial and temporal analysis of the N content and form in a water distribution network using reclaimed water for irrigating olive trees was performed. This study proved that changes in N were evident both over time and across the irrigation water distribution network. Seasonally, N content was reduced during the summer period. Spatially, a clear nitrification occurred from the pumping station to the farms. These variations demonstrate the importance of a continuous water quality control in order to adjust the fertilization plan according to the N content in water.

1. Introduction

Arid and semi-arid areas, such as Mediterranean countries, are already facing significant pressure on water resources. In the context of climate change, with the resulting increase in extreme weather events, and with the predicted growth in food demand, an exponential rise in that pressure is predicted (Bisselink et al., 2018). The use of non-conventional water sources, such as wastewater, and more specifically reclaimed water (RW), is one of the most sustainable alternatives to cope with water shortages and a key way to approach this problem (Iglesias and Garrote, 2015; Maestre-Valero et al., 2019b). Treated wastewater is water from any combination of domestic, industrial or commercial sources that has been processed in a wastewater treatment plant to remove contaminants (International Organization for Standardization, 2018). However, to make it appropriate for reuse, an additional treatment is necessary. Then, the former wastewater is called reclaimed or recycled water and it can be used for irrigation, enhancing water bodies among other uses (Raschid-sally and Jayakody, 2008). Worldwide, the countries that, according to Sato et al. (2013), reuse treated water the most are the USA (6.4 hm^3/day), Egypt (1.9 hm^3/day), Syria (1.5 hm^3/day), Spain (1.4 hm^3/day), Israel (0.7 hm^3/day) and Saudi Arabia (0.4 hm^3/day). Uses of RW vary largely, even within the same country, depending on the country's development, climate, main economic activities, etc. In general, it is estimated that, in developed countries and after secondary treatment, the main destination of these waters is agricultural irrigation (33%), followed by the irrigation of green areas (20%) and industrial uses (8%) (Prats-Rico, 2016). In a context where the agricultural sector is responsible for 70% of water abstractions worldwide, the use of treated wastewater for agricultural irrigation constitutes one of the basic strategies to manage imbalances between resource availability and demand. This also contributes to the promotion of the circular economy by recovering nutrients from the RW and applying them to crops, by means of fertigation techniques. Thus, water reuse could potentially reduce the need for supplemental applications of conventional fertilizers. Due to increasing interest, the application of this type of water to irrigate has already been evaluated

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by different authors. Some of them have focused their studies from a safety and environmental perspective (Chen et al., 2013; Kalavrouziotis et al., 2012; Lopez-Galvez et al., 2014). Others have paid more attention to the nutritional aspects (Maestre-Valero et al., 2019a; Pereira et al., 2011). There are also authors who have studied how RW could influence the development or quality of the crop (Lu et al., 2016). All of them agree with the fact that RW used as an irrigation water resource, if properly managed, does not result in adverse impacts and is safe for human health and the environment. At the same time, it could lead to significant fertilizer savings, since the application of additional fertilizers is reduced, increasing the yield and quality of the crops. Additionally, it may be essential for addressing both the water scarcity problem and irrigated agriculture sustainability enhancement.

Olive trees, the most iconic crop in the Mediterranean basin, have to adapt to the new political and institutional framework, both at national and international level, where a synergy between agricultural and environmental policies and the conservation of natural resources is taking place. In this sense, this crop represents a typical example of irrigation using RW resources and several authors have investigated its potential and effects. For example, Ashrafi et al. (2015) assessed the olive tree response in terms of growth, photosynthesis rates and nutrient content. They concluded that, thanks to the higher nutrient concentrations, plant development was improved. Erel et al. (2019) conducted a long-term study which demonstrated that olive nutrient requirements were covered using RW. They found that the olive trees nitrogen (N), phosphorus (P) and potassium (K) needs were met by irrigating with RW and without the use of additional fertilizer. Thanks to these nutrients, the RW irrigated trees also obtained higher fruit yields. However, they indicated that special attention must be paid to the soil which, over the long term, could suffer negative effects such as an increase in the ratio of sodium absorption. Salinity problems, nevertheless, were not found either in the soil or the olive trees. Pedrero et al. (2020) conducted a review considering different water sources and qualities, analyzing their benefits and limitations for olive tree irrigation. They affirmed that, in Mediterranean countries and over a long period, olive trees irrigated with RW are likely to improve their yield. However, they highlighted that, although N contribution through RW could be essential to achieve this greater production, it may also generate negative impacts on both olive yield and oil quality if given in excess. In addition, even though RW already contains N, Alcaide Zaragoza et al. (2019) confirmed that farmers keep applying significant fertilizer quantities without considering the negative environmental impacts and additional costs.

N is the main nutritional component of any crop and, therefore, of olive trees. For this reason, N has traditionally been the main mineral element used in olive fertilization plans. However, these plans are frequently based on farmer's experience which can lead to inappropriate N applications and, in many cases, over-fertilization (Fernández-Escobar, 2011). This can cause negative effects on crop health, quality and also the environment (Fernández-Escobar et al., 2006). Due to this importance, the N cycle and its implications in olive tree nutrition have been studied in the past. For example, Fernández-Escobar et al. (2012) estimated a N balance for olives, determining that an olive orchard had lower N requirements than historically thought. Traditionally, it was thought that annual N fertilizer applications were required for maintaining high yields. This research proved that depending on different factors (irrigation water quality, rainwater inputs, organic matter, etc.) N applications may not be necessary. The form in which N is applied is another important aspect to consider. Fertilizers can be in organic form, inorganic form (NH_4^+-N or NO_3^--N) or as a combination of both organic and inorganic. Depending on the crop, N is assimilated in one of its soluble forms, i.e., inorganic forms. In the case of the olive tree, it is able to assimilate N in both NH_4^+-N or NO_3^--N. However, differences in olive nutrition and impacts on the environment under the application of different N forms have been found. For instance, Tsabarducas et al. (2017) found differences in growth and photosynthesis rates in olive trees depending on the N form applied. Fernández-Escobar et al. (2004) also detected variations in N leaching depending on the N form used for fertilizing. However, all of them considered that the form of N arriving to the crop was the same as they were applying. In other words, none of them considered the influence of water quality parameters or the irrigation network characteristics on N form changes.

Irrigation district distribution networks usually cover large areas which involve big pipe lengths. Sometimes, particularly in areas devoted to one single crop, fertilizers are applied in the pumping station and distributed along the irrigation district through the water distribution network. Consequently, the travel time from the pump station to the plot hydrant is important, particularly to the furthest farms. This could entail unequal nutrient distribution to users. This effect was confirmed by Jimenez-Bello et al. (2011) at irrigation district level. They found considerable differences depending on the farm location. But they focused their attention on the irrigation network and considered that all the fertilizers injected in the network were received at farm level without changes in the water quality and concentration of nutrients. However, due to the RW particularities, some studies have proved that water quality changes inside the pipes. For example, Yu et al. (2020) studied the variability of the water quality parameters in river water replenished by RW. They found modifications in both the total N content and its inorganic forms (NH_4^+-N or NO_3^--N). Both Wang et al. (2016, 2020) conducted experiments under controlled conditions in order to investigate the relationship between the RW quality parameters and pipe length. They detected that pipe length had an important effect on the nitrification process. However, there are no studies that have assessed these effects on pressurized irrigation networks under real conditions.

N concentration in RW changes throughout the irrigation season and during the travel time within the irrigation network as a result of oxidation-reduction reactions, plot elevation differences, pipe length, etc. The N form which arrives at the farm influences both crop nutrition and N leaching. In this work, a spatial-temporal analysis of the N form changes in a water distribution network using RW for irrigation was carried out. Its implications in olive production and soil pollution were discussed.

2. Materials and methods

2.1. Case. study

The study was carried out in the Tintín Irrigation District (TID), located in Montilla (Córdoba, southern Spain). This region has a typical Mediterranean climate with an average annual rainfall of 590 mm, mostly during spring and autumn while they are almost negligible in summer. The daily mean temperature is 16.9 °C and the mean reference evapotranspiration, ET_0, 3 mm/day. However, ET_0 ranges from 0.5 mm/day during winter to 8 mm/day in summer. The water distributed for irrigation comes from the Montilla wastewater treatment plant (WWTP). Secondary treated wastewater (by extended aeration) and settled is diverted to the reclamation train, initially composed by a settling reservoir. Subsequently, the water is sent by communicating vessels to a larger reservoir for storage, where two ultrasound treatment units are installed for microalgae reduction. Before its distribution, the water, by floating intake, is sent to the filtration process composed of several automatic filter units (130 μm), self-cleaning by opening the ring pack (Fig. 1). Finally, some disinfectant treatments are applied: potassium permanganate ($KMnO_4$) was applied in both settling and storage reservoirs and peracetic acid ($C_2H_4O_3$) in the irrigation network. Particularly, 500 l of $KMnO_4$ were applied bimonthly and 900 l of $C_2H_4O_3$ were applied at the end of June. Thus, the water quality required for the irrigation of olive trees is achieved according to the Spanish regulation for water reuse (Spain Government, 2007). The TID water distribution network irrigates 150 ha within the Guadalquivir River basin where mainly olive is the cultivated crop. The average plot size is 1.5 ha. All the fields have the same irrigation system, subsurface drip irrigation with

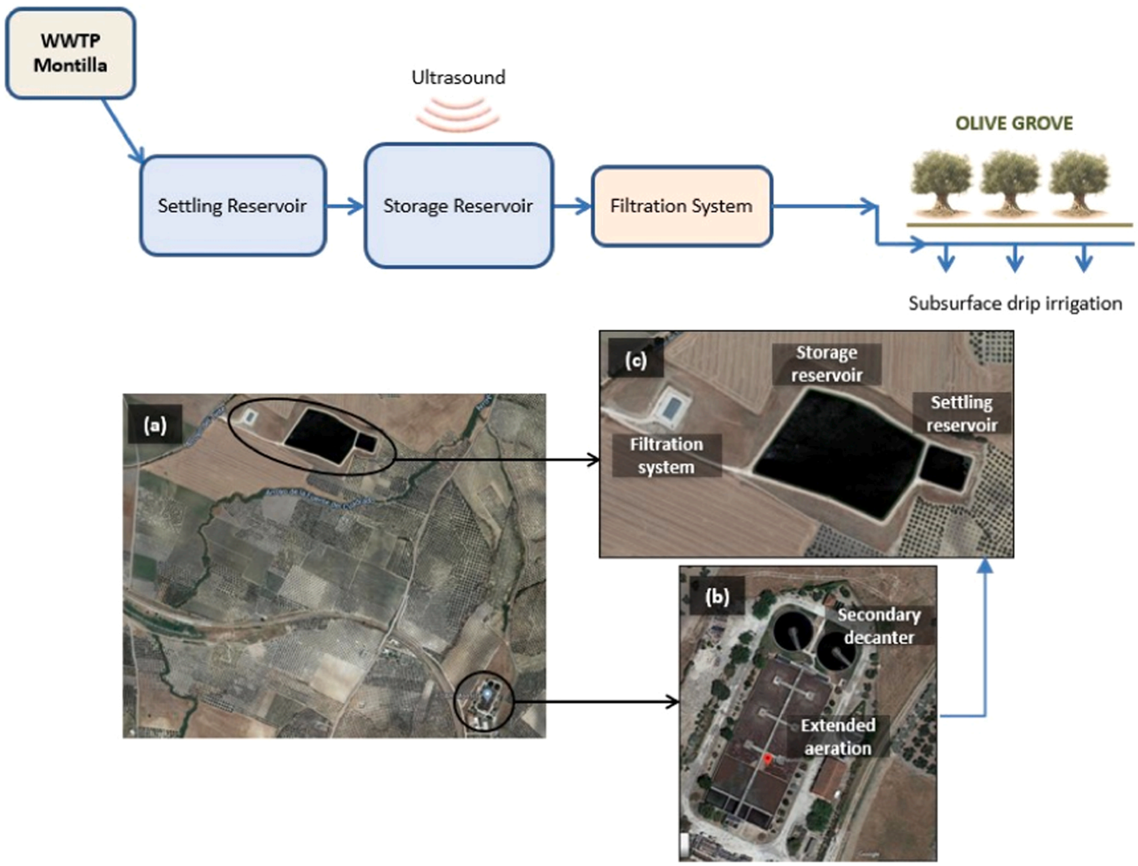

Fig. 1. (a) Aerial view of the complex Montilla WWTP - reclamation treatment in TID (Montilla, southern Spain); (b) Location of extended aeration and secondary decanter at the WWTP Montilla and (c) Aerial view of the reclamation treatment train installed in TID.

2.2 l·h^{-1} pressure compensating drippers spaced at 1 m and installed at a depth of 30 cm. The water allocation is 1500 m^3·year^{-1}·ha^{-1}. The irrigation season usually lasts between five and seven months depending on the rainfall of the year. Irrigation events are scheduled at district level by the irrigation district's manager and all the fields are irrigated simultaneously. The irrigation schedule consisted of applications four times a week for 8 h during the entire irrigation season. Irrigation was carried out every Tuesday, Thursday, Saturday and Sunday.

2.2. Sampling collection

Water quality analysis was carried out once a month during the 2019 irrigation season to assess the fluctuations in the N chemical forms throughout the year (temporal scale). They were measured before and after the filtration system (Filtration System Inlet – FSI and Filtration System Outlet – FSO) well as in two TID farms (F2 and F5). Later, the sample point number was extended in order to assess the spatial variability. Then, six strategic points across the irrigation network (F1 to F6) were selected to analyze the water quality they receive and the differences in the chemical forms of N (spatial scale). The farm points were selected according to their distance from the pumping station, elevation and pressure criteria. The characteristics of each sampling point are shown in Table 1. Differences between FSI and FSO made it possible to determine if additional fertilizer was being applied on the sampling days as well as the changes of N forms in the farms with respect to the pumping station. TID irrigation network and the selected points are shown in Fig. 2. In each sample, the total N (N_T) and different N forms were measured: ammoniacal nitrogen (NH_4^+-N), nitric nitrogen (NO_3^--N) and the N Total Kjeldhal (NTK). Organic N (N_{org}-N) was obtained as the difference between NTK and NH_4^+-N. Some other water quality parameters were also selected to be analyzed since they could influence the oxidation-reduction reactions and, therefore, the N form. Some particular bacteria are required for these reactions to take place which are highly susceptible to certain environmental factors, specifically to dissolved oxygen (DO) temperature (T) and pH, (Brion and Billen, 2000; Shammas, 1986). All of them need to be at optimal values for the reaction to occur. The chlorophyll a (Chl-a) content is another important parameter to analyze. It is related to the microalgae biomass which could affect the N content because of the microalgae consumption of N (Kuenzler et al., 1982). Finally, organic matter content can also affect the N form (Stein and Klotz, 2016) and, for that reason, the Chemical Oxygen Demand (COD) and the Biochemical Oxygen Demand (BOD_5) were measured. These parameters are indirect indicators of the organic

Table 1
Characteristics of the sampling points.

Sample point	Pipe length (m)	Elevation above the pumping station (m)	Pressure (m)
F1	1453	6	56
F2	3436	7	131
F3	3871	94	31
F4	4105	1	24
F5	6626	46	93
F6	6944	71	40

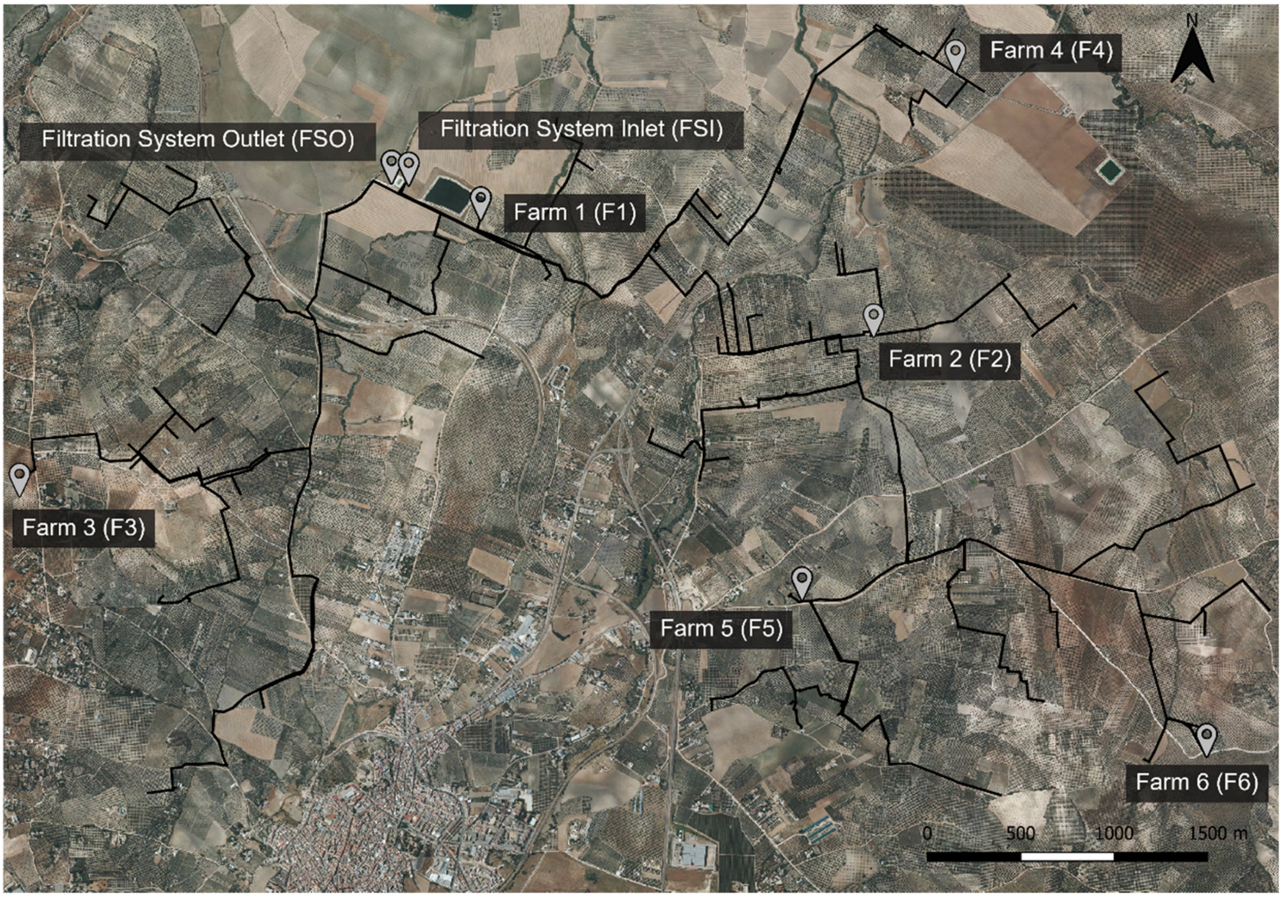

Fig. 2. Sampling point locations in TID (Montilla).

matter content in the water. The description and reference methods used for the analysis of the mentioned parameters in water samples are shown in Table 2.

Table 2
Description and reference methods used for the parameters analyzed in the water samples.

Parameter	Description	Reference method
Temperature (T)	Thermometry	S.M.[a]2550 B
pH	Electrometry	S.M. 4500H+ B
Dissolved oxygen (DO)	Electrometry	S.M. 4500-O G
Total nitrogen (N_T)	Digestion with potassium peroxydisulphate. Nitrophenol. Spectrophotometry.	APC228/338, methods DR3900EN ISO 11905-1
Ammoniacal nitrogen (NH_4^+-N)	Spectrophotometry. Salicylate, nitroprusside and indolphenol blue.	APC303, methods DR3900ISO 7150-1, DIN 38406 E5-1
Nitric nitrogen (NO_3^--N)	Spectophotometry. Dimethylphenol	APC339, methods DR3900ISO 7890-1-2-1986, DIN 38405 D9-2
Chlorophyll a (Chl-a)	Spectrophotometry. Methanol extraction	(Talling and Driver, 1963)
Chemical Oxygen Demand (COD)	Volumetry	S.M. 5220 C
Biochemical Oxygen Demand (BOD_5)	Incubation	S.M. 5210 B

[a] S.M.: Standard Methods for the Examination of Water and Wastewater,1989.

2.3. Data Analysis

Means and standard errors were obtained for each data. A Pearson correlation was performed to assess the relationships of the water quality parameters. Then, one-way repeated measures analysis of variance (RM ANOVA) was carried out for the temporal analysis. This analysis is suitable for data in which the same variables are measured more than once (Davis, 2002). RM ANOVA must fulfill the sphericity condition which was analyzed using the Maulchy test. When the sphericity condition was not confirmed, the Greenhouse-Geisser correction was applied to be able to continue with the RM ANOVA. For spatial analysis, the difference between the N concentration on the farms and the N concentration at FSO was performed for each N form and each period. All the analysis were performed in R programming language using RStudio as the integrated development environment (IDE) for Windows (Van der Loo and De Jonge, 2012).

3. Results and discussion

3.1. Water quality characterization

Results of the water quality parameters analyzed in the eight sampling points during the 2019 irrigation season in TID are shown in Table 3. N_T ranged from 21.8 mg·l^{-1} to 3.3 mg·l^{-1} which implied an important difference between some water samples. This quantity of N_T was similar to other RW used for olive tree irrigation (Bourazanis et al.,

Table 3
Water quality parameters analyzed in TID during 2019 irrigation season (n = 39).

Parameter	Max	Min	Mean	SD
N_T (mg·l^{-1})	21.8	3.3	10.7	5.0
NH_4^+– N (mg·l^{-1})	13.5	0.0	5.3	4.5
NO_3^- – N (mg·l^{-1})	8.0	0.1	2.5	1.8
N_{org}-N (mg·l^{-1})	7.6	0.0	2.9	1.6
pH	9.0	7.1	7.9	0.5
DO (mg·l^{-1})	12.0	0.9	5.0	2.8
T (ºC)	28.1	19.3	24.7	2.5
Chl-a (µg·l^{-1})	303.4	0.7	64.4	61.3
COD (mg/l O_2)	79.0	22.0	41.7	13.2
BOD_5 (mg/l O_2)	17.0	0.0	6.7	4.0

2016; Petousi et al., 2015; Segal et al., 2011). On average, the NH_4^+– N concentration was higher than NO_3^-– N. As for N in nitrite form, this was not found during the experiment, being the rest of the N_T in organic form. The value of the pH during the whole season was considered as slightly alkaline with an average value of 7.8. DO and Chl-a also changed largely during the experiment. These parameters can affect both the amount of N_T and also its form (Cira et al., 2016; Espinosa Rodríguez et al., 2014). In the case of water temperature, its variation may be caused by the fluctuation in the environment temperature. The results of both COD and BOD_5 met the minimum quality requirements for water reuse established in the EU Regulation (The European Parliament and the Council of the European Union, 2020), which are 125 mg/l O_2 and 25 mg/l O_2, respectively.

Table 4 shows the Pearson correlation applied to the water quality parameters analyzed. N_T was positive correlated to both NH_4^+-N and NO_3^--N. All the analyzed parameters, except for DO, were significantly correlated to the N content or its form. Although no correlation was observed between either COD or BOD_5 and the total N content, different correlations were found with the different chemical forms. Specifically, both showed a significant positive correlation with N_{org}-N, which is expected since these parameters are indicators of the organic matter in the water. In addition, a significant positive correlation between BOD_5 and NO_3^--N was found as well as a significant negative correlation with NH_4^+-N, which may indicate that BOD_5 could be affecting nitrification. Chl-a is used as an indicator of microalgae biomass (Desortová, 1981) which could explain its negative correlation with N content due to the consumption of this nutrient by microalgae (Kuenzler et al., 1982). Both pH and T were also influential parameters for N_T and NH_4^+-N. This may indicate that nitrification was occurring (Shammas, 1986). Finally, there was not a noticeable correlation between the pipe length and the total content in N. However, a positive significant correlation was found between pipe length and NO_3^--N in contrast with the negative correlation found for NH_4^+-N. This may suggest that a nitrification process was occurring throughout the irrigation network, which matches the information given by Wang et al. (2016).

3.2. Temporal analysis

Fig. 3(a) shows the results for the different N forms at the inlet and the outlet of the filtration system. According to this graph no substantial differences between FSI and FSO were detected, except in May. In this month, there was a decrease of N_T after the filtration treatment. This reduction was mainly caused by an organic N drop. In all other cases, neither N_T nor the N forms changed meaningfully. No additional fertilizer was applied during the sampling days and, therefore, the irrigation water quality was only determined by the water source quality. However, changes in N_T and the N forms can be observed over time. During May, June and July, a higher N_T concentration was found. In these months, N was mostly in ammonium form, with a concentration around 30% higher than in the remaining months. NO_3^--N concentration had approximately the same value during all the season excluding October, when it was nearly zero. Finally, for the remaining N, i.e., N_{org}-N, its concentration was not steady throughout the season.

As mentioned before, the Chl-a content is related to the phytoplanktonic biomass. The highest values of Chl-a were obtained in August, September and October which matched the lowest N_T contents (Fig. 3(b)). This confirmed that the absorption and utilization of phytoplankton in the storage reservoir was an important reason for N_T reduction throughout the irrigation season. This is consistent with previous results found by Yu et al. (2020). Regarding the Chl-a trend over time, it is important to highlight that phytoplankton growing is promoted by light and temperatures (Geider, 1987). Because of that, a growing content was determined from May to September. However, during July, when temperatures were highest, the Chl-a concentration dropped to values of nearly zero. It is important to highlight that, in order to increase filtration system efficiency, potassium permanganate was applied to the storage reservoir. This treatment was complemented with the ultrasound treatment which, according to numerous scientific studies, has an important anti-algae effect (Jachlewski et al., 2013; Joyce et al., 2010; Wu et al., 2011).

RM ANOVA was calculated for the water quality parameters of the samples collected at the farms. As a result, *p*-value was less than 0.05 for all the parameters analyzed. In other words, all the water quality variables measured at farm level changed significantly throughout the 2019 irrigation season. Fig. 4 showed the mean and standard error of the different N form at the analyzed farms. If both Fig. 3(a) and Fig. 4 are compared, it is observed that the N_T remained steady from FSO to the farms. This implies that the total N content was mainly determined by the water quality source. The N_T concentration peaked in June amounting to 19.7 mg·l^{-1} (Fig. 3(a)), a 63% higher than in August, when the lowest N_T content was measured (7.1 mg·l^{-1}). The average nitrate concentration detected at farm level was around 3.4 mg·l^{-1} except in June with a maximum average concentration of 6.8 mg·l^{-1}, and in October with a minimal of 0.6 mg·l^{-1} (Fig. 4). As for ammonium, its concentration varied largely in the irrigation season. This variation

Table 4
Pearson correlation of the water quality parameters in TID during 2019 irrigation season.

Parameter	N_T	NH_4^+– N	NO_3^- – N	N_{org} – N	pH	DO	T	Chl-a	COD	BOD_5	Pipe length
N_T (mg·l^{-1})	1										
NH_4^+– N (mg·l^{-1})	0.82***	1									
NO_3^- – N (mg·l^{-1})	0.40*	-0.16	1								
N_{org} – N (mg·l^{-1})	0.37*	0.34*	0.15	1							
pH	0.45**	0.53***	-0.17	0.13	1						
DO (mg·l^{-1})	0.07	0.08	-0.10	-0.12	0.62***	1					
T (ºC)	-0.44**	-0.55***	0.26	-0.04	-0.19	-0.14	1				
Chl-a (µg·l^{-1})	-0.54***	-0.62***	-0.10	-0.25	-0.32	-0.09	0.32*	1			
COD (mg/l O_2)	0.02	-0.29	0.31	0.56***	0.08	0.18	0.17	0.58***	1		
BOD_5 (mg/l O_2)	0.00	-0.36*	0.60***	0.41*	0.05	0.24	0.35*	0.17	0.52***	1	
Pipe length (m)	-0.13	-0.34*	0.47**	0.06	-0.59***	-0.52***	0.27	0.13	0.04	0.12	1

*: significant correlation at $p < 0.05$;**: significant correlation at $p < 0.01$; ***: significant correlation at $p < 0.001$.

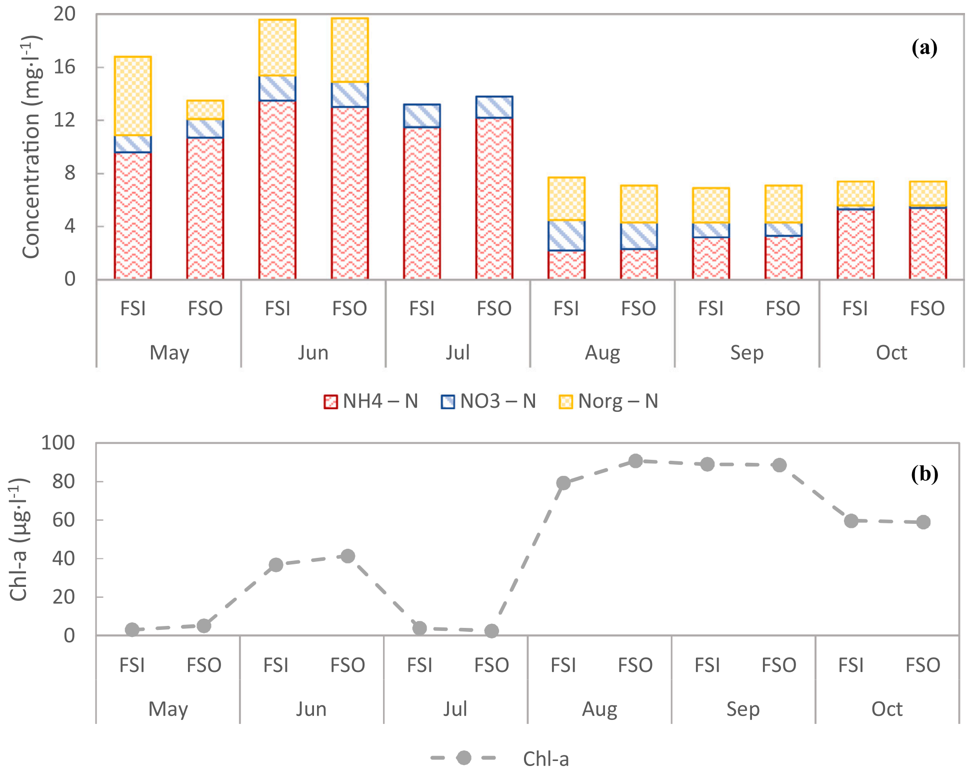

Fig. 3. Different N forms (a) and Chl-a (b) variations before and after filtration system of TID during 2019 irrigation season.

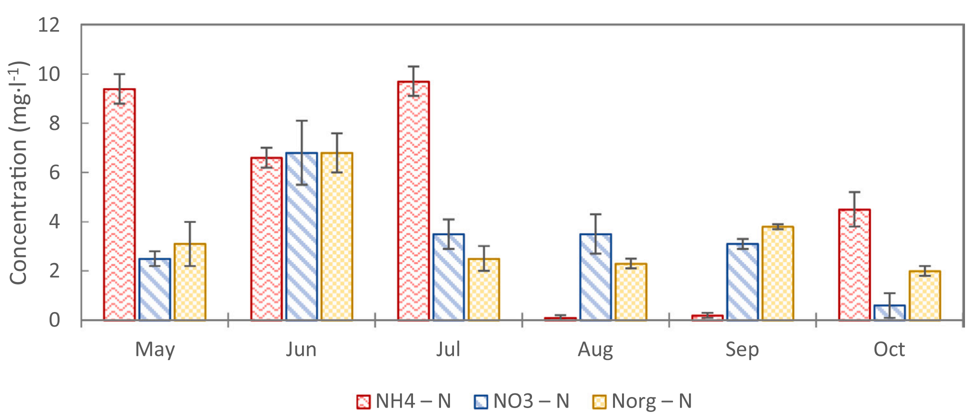

Fig. 4. Mean and standard error of the N forms in the samples collected at the farms during 2019 irrigation season.

matched with the variation at FSO: highest concentration in May, June and July; medium content in October and nearly zero in August and September. Besides the parameter itself, the proportion of each N form also changed over time. Fig. 3 shows that during May, June and October the majority of the N was in ammonium form in contrast to July and August when the NO_3^- – N and N_{org}– N proportions were higher. However, June was the only month in which the proportion was similar for the three N forms. These results highlight the importance of a regular control when RW is used for irrigating olive trees. The fertilization plan must be adjusted and modified depending on the water quality.

Table 5
Total inorganic N arriving to the farms during 2019 irrigation season.

	NH_4^+-N (mg·l^{-1})						NO_3^--N (mg·l^{-1})					
	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6
May	–	9.9	–	–	8.8	–	–	2.1	–	–	2.8	–
June	–	6.9	–	–	6.2	–	–	5.5	–	–	8	–
July	11.1	10.2	11	7.9	8.8	8.6	2.6	3.2	2.2	5.2	2.1	4.6
August	0	0	0	0	0	0.3	4.5	4.6	4.7	5	2.4	0.9
September	0.2	0.4	0.4	0.1	0.3	0	2.8	2.9	3	3.8	2.9	3.3
October	5	5.4	–	5.4	2.3	5.1	0.2	0.1	–	0.1	2.6	0.1

3.3. Spatial analysis

Total inorganic N (NH_4^+-N and NO_3^--N) arriving at the farms is shown in Table 5. Modifications in inorganic N across the TID network were also determined (Fig. 5(a)). These modifications were calculated as the difference between concentrations arriving at the farms and concentrations at FSO. Nitrate concentration increased across the irrigation network in contrast to the reduction observed in the ammoniacal forms. These modifications are usually interrelated, which confirms a nitrification process is occurring. Nitrification is a very complex process in which the nitrifying bacteria transform the ammonium ion into nitrate ion (Rittmann and McCarty, 2001). RW generally has an elevated content of these bacteria which are highly susceptible to certain environmental factors, specifically to pH, DO and T (Brion and Billen, 2000; Shammas, 1986). The modifications in these parameters during 2019 are also shown in Fig. 5(b), (c) and (d) respectively.

In general, Table 5 shows that in May, June, July and October the reduced forms (ammonium) were in higher concentration than the oxidized ones (nitrates). Only in August and September is this pattern reversed. Fig. 5(a) shows an uneven nitrification throughout the irrigation season. For that reason, the influential parameters were analyzed previously. Regarding pH, Fig. 5(b) shows that pH varied from 9 to 7. The optimal value for the nitrification process is 8, while pH values below 6.5 reduce the nitrification rate significantly (Shammas, 1986). Therefore, pH values in TID were suitable for the nitrification process. This reaction consumes alkalinity, since it reduces the HCO_3^- content and increases H_2CO_3, which decreases the pH (Rittmann and McCarty, 2001). This is consistent with the information observed in Fig. 5(a) and

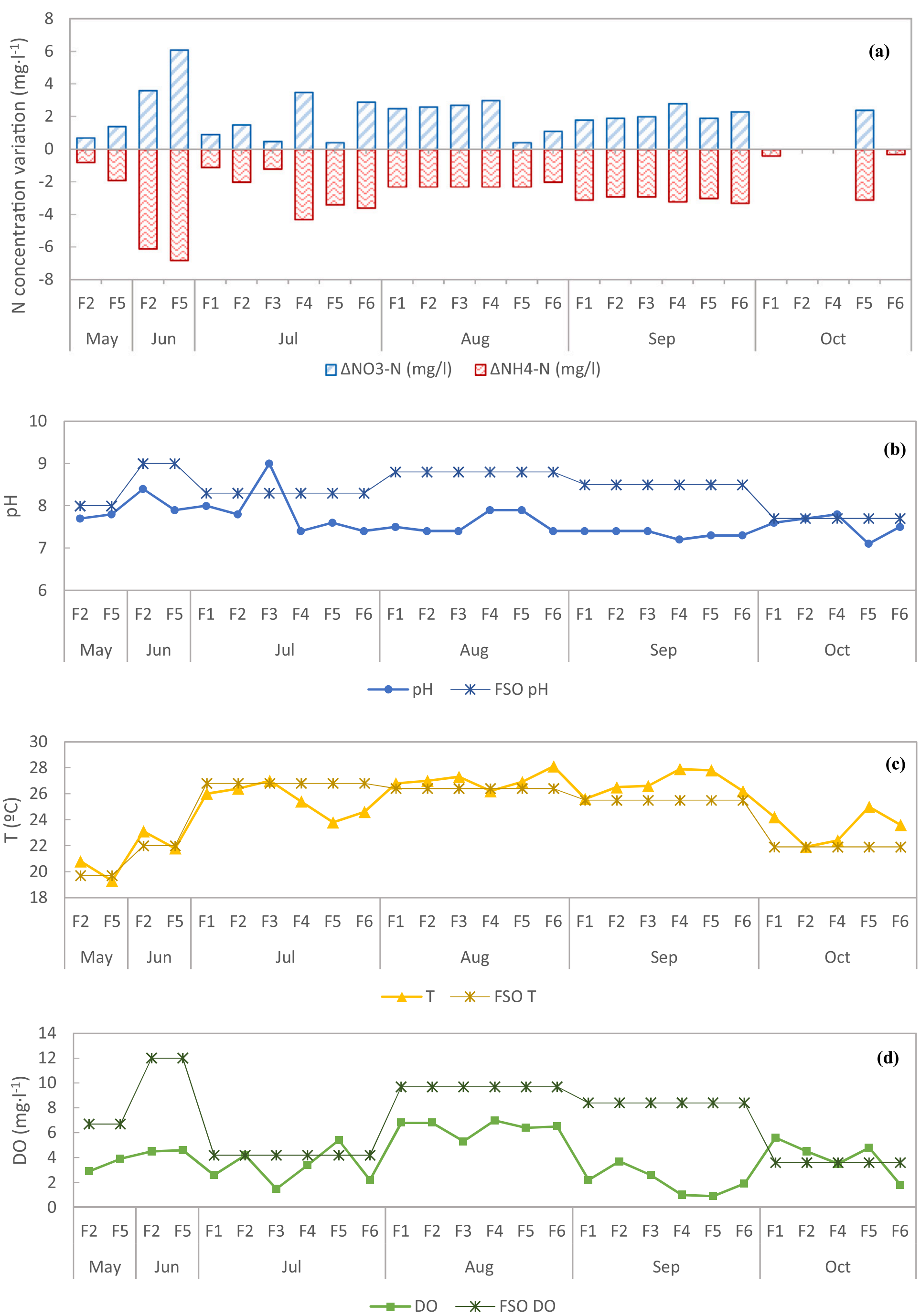

Fig. 5. Variations across the TID irrigation network in: (a) inorganic N (mg·l-1); (b) pH; (c) T (ºC) and DO (mg·l-1).

(b), in which the pH decreased at farms where NH_4^+-N transformation into NO_3^--N occurred. This pH reduction was around 1 as average from FSO. As for T, the nitrification process can occur from 15 to 35 ºC, with 30 ºC being the optimal temperature (Shammas, 1986). Fig. 5(c) shows that during July, August and September water temperatures were higher (around 26.5 ºC) compared to May, June or October when temperatures were 22 ºC on average. There were no important modifications in T from FSO and the farms. Finally, considering DO concentrations, values below 4 $mg \cdot l^{-1}$ indicates a slowdown of nitrification rate until less than 2 $mg \cdot l^{-1}$ when this rate drops significantly (Espinosa Rodríguez et al., 2014). Fig. 5(d) shows that at FSO, DO concentration were above 4 $mg \cdot l^{-1}$ in May, June, August and September, in contrast with July and October when its value was about 4, which can compromise the nitrification process. DO arriving at the farms also decreased when nitrification occurred due to its use during this reaction.

Therefore, during May and June part of the NH_4^+-N turned into NO_3^--N from FSO to the farms (Fig. 5(a) and Table 5). Information related to the farm distances are shown in Table 1. In June this transformation was probably higher because of the higher temperature and DO content than in May. In both cases, nitrification was higher in F5 which was further than F2, which may indicate the influence of distance, and therefore the travel time of the water, in the N form arriving at farms. This matches the results found by Wang et al. (2020) who found a clear relationship between nitrification and pipes length. During August and September, the ammonium transformations to nitrate were more similar between the farms. T, DO and pH were in appropriate ranges in t these months for the nitrifying bacteria. However, these were the months in which N_T was lower and nitrification occurred until the entire $NH4^+$-N removal as shown in Table 5. Finally, in July and October, the nitrification process was irregular along the farms. In both months, DO concentration at FSO was significantly lower than in other months, around 4 $mg \cdot l^{-1}$, which compromised the oxidation reaction. In October, T was also lower which can also affect this reaction.

3.4. Implications of using RW for olive tree irrigation

The N form arriving at the farm affects both the olive grove growth and the environment. This work proved that important changes in both N form and total N content took place in TID during the 2019 irrigation season. Removal of N and nitrification were produced both temporally and spatially. Considering the irrigation schedule of TID and the results of the water quality analyses, the total N applied was estimated at 19.6 $kg \cdot ha^{-1}$ during the irrigation season. According to Fernández-Escobar et al. (2012), who estimated the N extractions and inputs in olive grove, that quantity was enough to cover olive N requirements. This means that, in this particular case, no additional fertilizers would be needed. However, farmers applied additional fertilizers as their fertilization management is based on traditional methods and they do not consider the nutrients carried in water (Alcaide Zaragoza et al., 2019). This results in overfertilization, which causes numerous negative effects: reduction in yield, oil quality and frost tolerance as well as water pollution problems (Fernández-Escobar et al., 2009, 2006). As for N distribution, different authors affirmed that the more distributed the N applications, the higher the N efficiency (Fernández-Escobar et al., 2004). Thanks to the nutrients going through RW, the N application was continuous and distributed over time. However, the total quantity arriving at the farms was not steady. This proved the importance of a periodic water quality control and of a real-time fertilization dose adjustment to that quality. The supply of N through RW must be considered when carrying out additional fertilization programs since, if necessary, they should supplement the N already dissolved in the water. This could be a complex task for farmers on a day-to-day basis. However, thanks to advances in technology nowadays, there are tools or Apps for mobiles that can help farmers to do that in an easy way, such as that developed by Alcaide Zaragoza et al. (2020).

Considering N form, this work also proved that pipe length and abiotic factors could influence the final form arriving at the farms. Fernández-Escobar et al. (2004) affirmed that the olive tree growth was adequate regardless the N form used as long as the applied dose of fertilizer was correct. However, if N form did not change, it could create some problems. For example, excessive application in the ammonium form could acidify the rhizosphere and cause Ca, Mg or K absorption problems (Fernández-Escobar, 2017). Tsabarducas et al. (2017) also found that an excess in ammonium use inhibited the photosynthetic ratio of olive trees. On the other hand, nitrate is easily used by the olive trees when the application dose is low. But, given in excess, it can cause a drop in P, Fe, Mn and Zn concentrations as well as leaching problems. In fact, NO_3^--N is the main form of N leaching which is one of the major concerns facing sustainable agriculture. N leaching is exacerbated by rain events. However, in this work, the highest amount of nitrate reached the farms during the summer months, when rain fall is less likely, which entailed less nitrate leaching risk during the rainy season. In any case, the nitrate concentration did not exceed the harmful quantity to the environment (Spanish Government, 1996). Influence of the farm distance in the arriving N form could be valuable guidance for managers in order to avoid leaching or other nutrient absorption problems. In this particular case, the changes produced in N temporally and spatially prevented the aforementioned problems related to the constant N form. Finally, the nitrification process also entailed modifications in some other water quality parameters which could influence the olive irrigation, particularly, pH. The water pH could influence the emergence of plugging problems in the irrigation system. García Zamorano et al. (2004) established the chemical plugging risk as high when pH was higher than 8. Then, in those farms in which nitrification occurred, the plugging risk was reduced without the need to apply additional products.

4. Conclusions

A spatial and temporal analysis of N content and form in reclaimed water used for olive tree irrigation was carried out. This study proved that, due to the characteristics of the RW, changes in N were produced both over time and across the irrigation water distribution network. The temporal changes were strongly linked to the content in Chl-a which was not related to the distribution network but to the storage reservoir. The concentration of algal biomass in the water was one of the regulatory factors of the total content of N arriving at the farms. Spatially, a clear nitrification occurred from the pumping station to the farms. This reaction was determined by the pH, T and DO values of the water in the pumping station. In most cases, part or the totality of the ammonium was converted into nitrate.

This study confirmed that, due to the quantity of N found in the RW, olive tree requirements were covered. The temporal and spatial changes of N form allowed for the avoidance of problems related to the same N form in olives trees. In addition, these changes demonstrate the importance of a continuous water quality control to adjust the fertilization plan to the N content in water. For all that, this work confirms that irrigation with RW is a sustainable alternative for olive grove irrigation.

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.

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References

Alcaide Zaragoza, C., Fernández García, I., González Perea, R., Camacho Poyato, E., Rodríguez Díaz, J.A., 2019. REUTIVAR: Model for precision fertigation scheduling for olive orchards using reclaimed Water. Water 11. https://doi.org/10.3390/w11122632.

Alcaide Zaragoza, C., González Perea, R., Fernández García, I., Camacho Poyato, E., Rodríguez Díaz, J.A., 2020. Open source application for optimum irrigation and fertilization using reclaimed water in olive orchards. Comput. Electron. Agric. 173. https://doi.org/10.1016/j.compag.2020.105407.

Ashrafi, N., Nikbakht, A., Gheysari, M., Fernández-Escobar, R., Ehtemam, M.H., 2015. Effect of a new irrigation system using recycled water on stomatal behaviour, photosynthesis and nutrient uptake in olive trees (Olea europaea L.). J. Hortic. Sci. Biotechnol. 90, 401–406. https://doi.org/10.1080/14620316.2015.11513201.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., Roo, A., De, 2018. Impact of a Changing Climate, Land Use, and Water Usage on Europe's Water Resources. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/09027. JRC Technical Report EUR 29130, ENJRC110927.

Bourazanis, G., Roussos, P.A., Argyrokastritis, I., Kosmas, C., Kerkides, P., 2016. Evaluation of the use of treated municipal waste water on the yield, oil quality, free fatty acids' profile and nutrient levels in olive trees cv Koroneiki, in Greece. Agric. Water Manag. 163, 1–8. https://doi.org/10.1016/j.agwat.2015.08.023.

Brion, N., Billen, G., 2000. Wastewater as a source of nitrifying bacteria in river systems: the case of the River Seine downstream from Paris. Water Res. 34, 3213–3221. https://doi.org/10.1016/S0043-1354(00)00075-0.

Chen, W., Lu, S., Jiao, W., Wang, M., Chang, A.C., 2013. Reclaimed water: a safe irrigation water source? Environ. Dev. 8, 74–83. https://doi.org/10.1016/j.envdev.2013.04.003.

Cira, E.K., Paerla, H.W., Wetza, M.S., 2016. Effects of nitrogen availability and form on phytoplankton growth in a eutrophied estuary (Neuse River Estuary, NC, USA). PLoS One 11, 1–15. https://doi.org/10.1371/journal.pone.0160663.

Davis, C.S., 2002. Normal-Theory Methods: Repeated Measures ANOVA, in: Casella, G., Fienberg, S., Olkin, I. (Eds.), Statistical Methods for Analysis of Repeated Measurements. Springer-Verlag New York, Inc., 175 Fifth Avenue, New York, NY 10010, USA, pp. 103–123.

Desortová, B., 1981. Relationship between chlorophyll-a concentration and phytoplankton biomass in several reservoirs in Czechoslovakia. Int. Rev. Gesamt Hydrobiol. Hydrogr. 66, 153–169. https://doi.org/10.1002/iroh.19810660202.

Erel, R., Eppel, A., Yermiyahu, U., Ben-Gal, A., Levy, G., Zipori, I., Schaumann, G.E., Mayer, O., Dag, A., 2019. Long-term irrigation with reclaimed wastewater: implications on nutrient management, soil chemistry and olive (Olea europaea L.) performance. Agric. Water Manag. 213, 324–335. https://doi.org/10.1016/j.agwat.2018.10.033.

Espinosa Rodríguez, M., Bravo Bolaños, O., Ortega Aguirre, J., Hidalgo Millán, A., 2014. Evaluación de la nitrificación a través de perfiles operacionales en un reactor aerobio. Ingenierías 17, 50–59.

Fernández-Escobar, R., 2017. Fertilización, in: El Cultivo Del Olivo. pp. 419–460. (in Spanish).

Fernández-Escobar, R., 2011. Use and abuse of nitrogen in olive fertilization. Acta Hortic. 888, 249–258. https://doi.org/10.17660/actahortic.2011.888.28.

Fernández-Escobar, R., Beltrán, G., Sánchez-Zamora, M.A., García-Novelo, J., Aguilera, M.P., Uceda, M., 2006. Olive oil quality decreases with nitrogen over-fertilization. HortScience 41, 215–219. https://doi.org/10.21273/HORTSCI.41.1.215.

Fernández-Escobar, R., Benlloch, M., Herrera, E., García-Novelo, J.M., 2004. Effect of traditional and slow-release N fertilizers on growth of olive nursery plants and N losses by leaching. Sci. Hortic. 101, 39–49. https://doi.org/10.1016/j.scienta.2003.09.008.

Fernández-Escobar, R., García-Novelo, J.M., Molina-Soria, C., Parra, M.A., 2012. An approach to nitrogen balance in olive orchards. Sci. Hortic. 135, 219–226. https://doi.org/10.1016/j.scienta.2011.11.036.

Fernández-Escobar, R., Marin, L., Sánchez-Zamora, M.A., García-Novelo, J.M., Molina-Soria, C., Parra, M.A., 2009. Long-term effects of N fertilization on cropping and growth of olive trees and on N accumulation in soil profile. Eur. J. Agron. 31, 223–232. https://doi.org/10.1016/j.eja.2009.08.001.

García Zamorano, F., Ruiz Coleto, F., Cano Rodríguez, J., Pérez García, J., Molina de la Rosa, J.L., 2004. Suelo, riego, nutrición y medio ambiente del olivar. Junta de Andalucía. Servicio de Publicación y Divulgación, Sevilla. (in Spanish).

Geider, R.J., 1987. Light and temperature dependence of the carbon to chlorophyll a ratio in miroalgae and cyanobateria: implications for physiology and growth of phytoplankton. N. Phytol. 106, 1–34. https://doi.org/10.1111/j.1469-8137.1987.tb04788.x.

Iglesias, A., Garrote, L., 2015. Adaptation strategies for agricultural water management under climate change in Europe. Agric. Water Manag. 155, 113–124. https://doi.org/10.1016/j.agwat.2015.03.014.

International Organization for Standardization, 2018. ISO 20670:2018, Water reuse - Vocabulary.

Jachlewski, S., Botes, M., Cloete, T.E., 2013. The effect of ultrasound at 256 KHz on Microcystis aeruginosa, with and without gas vacuoles. Water SA 39, 171–174. https://doi.org/10.4314/wsa.v39i1.17.

Jimenez-Bello, M.A., Martínez, F., Bou, V., Bartolín, H., 2011. Analysis, assessment, and improvement of fertilizer distribution in pressure irrigation systems. Irrig. Sci. 29, 45–53. https://doi.org/10.1007/s00271-010-0215-7.

Joyce, E.M., Wu, X., Mason, T.J., 2010. Effect of ultrasonic frequency and power on algae suspensions. J. Environ. Sci. Heal. - Part A Toxic/Hazard. Subst. Environ. Eng. 45, 863–866. https://doi.org/10.1080/10934521003709065.

Kalavrouziotis, I.K., Koukoulakis, P., Kostakioti, E., 2012. Assessment of metal transfer factor under irrigation with treated municipal wastewater. Agric. Water Manag. 103, 114–119. https://doi.org/10.1016/j.agwat.2011.11.002.

Kuenzler, E.J., Stone, K.L., Albert, D.B., 1982. Phytoplankton uptake and sediment release of nitrogen and phosphorus in the Chowan River. North Carol. Rep. 186.

Stein, L.Y., Klotz, M.G., 2016. The nitrogen cycle. Curr. Biol. 26, 94–98. https://doi.org/10.1016/j.cub.2015.12.021.

Lopez-Galvez, F., Allende, A., Pedrero-Salcedo, F., Alarcon, J.J., Gil, M.I., 2014. Safety assessment of greenhouse hydroponic tomatoes irrigated with reclaimed and surface water. Int. J. Food Microbiol. 191, 97–102. https://doi.org/10.1016/j.ijfoodmicro.2014.09.004.

Lu, S., Zhang, X., Liang, P., 2016. Influence of drip irrigation by reclaimed water on the dynamic change of the nitrogen element in soil and tomato yield and quality. J. Clean. Prod. 139, 561–566. https://doi.org/10.1016/j.jclepro.2016.08.013.

Maestre-Valero, J.F., Gonzalez-Ortega, M.J., Martinez-Alvarez, V., Gallego-Elvira, B., Conesa-Jodar, F.J., Martin-Gorriz, B., 2019a. Revaluing the nutrition potential of reclaimed water for irrigation in southeastern Spain. Agric. Water Manag. 218, 174–181. https://doi.org/10.1016/j.agwat.2019.03.050.

Maestre-Valero, J.F., González-Ortega, M.J., Martínez-Álvarez, V., Martin-Gorriz, B., 2019b. The role of reclaimed water for crop irrigation in southeast Spain. Water Sci. Technol. Water Supply 19, 1555–1562. https://doi.org/10.2166/ws.2019.024.

Pedrero, F., Grattan, S.R., Ben-Gal, A., Vivaldi, G.A., 2020. Opportunities for expanding the use of wastewaters for irrigation of olives. Agric. Water Manag. 241, 106333 https://doi.org/10.1016/j.agwat.2020.106333.

Pereira, B.F.F., He, Z.L., Stoffella, P.J., Melfi, A.J., 2011. Reclaimed wastewater: effects on citrus nutrition. Agric. Water Manag. 98, 1828–1833. https://doi.org/10.1016/j.agwat.2011.06.009.

Petousi, I., Fountoulakis, M.S., Saru, M.L., Nikolaidis, N., Fletcher, L., Stentiford, E.I., Manios, T., 2015. Effects of reclaimed wastewater irrigation on olive (Olea europaea L. cv. 'Koroneiki') trees. Agric. Water Manag. 160, 33–40. https://doi.org/10.1016/j.agwat.2015.06.003.

Prats-Rico, D., 2016. Reuse of purified regenerated water worldwide: analyzes and projections. Water Landsc. 8, 10–21. https://doi.org/10.17561/at.v0i8.3292.

Raschid-sally, L., Jayakody, P., 2008. Drivers and Characteristics of Wastewater Agriculture in Developing Countries: Results from a Global Assessment. International Water Management Institute. IWMI, Colombo, Sri Lanka https://doi.org/http://dx.doi.org/10.3910/2009.127.

Rittmann, B.E., McCarty, P.L., 2001. Environmental biotechnology: principles and applications. Boston McGraw-Hill.

Sato, T., Qadir, M., Yamamoto, S., Endo, T., Zahoor, A., 2013. Global, regional, and country level need for data on wastewater generation, treatment, and use. Agric. Water Manag. 130, 1–13 https://doi.org/10.1016/j.agwat.2013.08.007.

Segal, E., Dag, A., Ben-Gal, A., Zipori, I., Erel, R., Suryano, S., Yermiyahu, U., 2011. Olive orchard irrigation with reclaimed wastewater: agronomic and environmental considerations. Agric. Ecosyst. Environ. 140, 454–461. https://doi.org/10.1016/j.agee.2011.01.009.

Shammas, N.K., 1986. Interactions of temperature, pH and biomass on the nitrification process. Water Pollut. Control Fed. 58, 52–59. ⟨http://www.jstor.org/stable/25042841⟩.

Spain Government, 2007. Royal Decree 1620/2007, de 7 de diciembre, por el que se establece el régimen jurídico de la reutilización de las aguas depuradas. Spain. (in Spanish).

Spanish Government, 1996. Royal Decree 261/1996 sobre Protección De Las Aguas Contra La Contaminación Producida Por Los Nitratos Procedentes De Fuentes Agrarias, BOE num. 61. (in Spanish).

Talling, J.F., Driver, D., 1963. Some problems in the estimation of chlorophyll-a in phytoplankton, in: Proceedings of the Conference of Primary Productivity Measurement, Marine and Freshwater. University of Hawaii, Honolulu, Atomic Energy Commission TID-7633,pp. 142–146.

The European Parliament and the Council of the European Union, 2020. Regulation (EU) 2020/741, Minimun requirements for water reuse, Official Journal of the European Union.

Tsabarducas, V., Chatzistathis, T., Therios, I., Patakas, A., 2017. How nitrogen form and concentration affect growth, nutrient accumulation and photosynthetic performance of Olea europaea L. (cv. 'Kalamon'). Sci. Hortic. 218, 23–29. https://doi.org/10.1016/j.scienta.2017.02.012.

Van der Loo, M.P.J., De Jonge, E., 2012. Learning RStudio for R Statistical Computing Learn to Effectively Perform R Development, Statistical Analysis and Reporting with the Most Popular R IDE. Packt Pub., Birm., UK.

Wang, Y., Ke, L., Pei, L.Y., Fan, L.Y., Nan, Y.P., Peng, D.C., Xia, S.Q., 2016. Nitrification in a model distribution system fed with reclaimed water from a wastewater treatment plant. Clean Soil Air Water 44, 263–271. https://doi.org/10.1002/clen.201300370.

Wang, Y., Wang, W.H., Wang, R.Q., 2020. Simultaneous nitrification and denitrification in biofilm of a model distribution pipe fed with disinfected reclaimed water. J. Water Process Eng. 35. https://doi.org/10.1016/j.jwpe.2020.101207.

Wu, X., Joyce, E.M., Mason, T.J., 2011. The effects of ultrasound on cyanobacteria. Harmful Algae 10, 738–743. https://doi.org/10.1016/j.hal.2011.06.005.

Yu, Y., Song, X., Zhang, Y., Zheng, F., 2020. Assessment of water quality using chemometrics and multivariate statistics: a case study in Chaobai. Water 12, 1–23.