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Review

Opportunities for expanding the use of wastewaters for irrigation of olives

Francisco Pedrero[a,*], S.R. Grattan[b], Alon Ben-Gal[c], Gaetano Alessandro Vivaldi[d]

[a] Department of Irrigation, CEBAS-CSIC, Campus Universitario de Espinardo, 30100, Murcia, Spain
[b] Department of Land, Air and Water Resources, University of California, Davis, 95616, USA
[c] Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, Gilat Research Center, M.P. Negev, 85280, Israel
[d] Dipartimento di Scienze Agro-Ambientali e Territoriali, Università Degli Studi Di BariAldo Moro, Via Amendola 165/A, 70126 Bari, Italy

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ABSTRACT

Olive trees are iconic to the Mediterranean landscape and in recent times, have expanded to other regions across the globe that share similar climatic conditions. Olive oil production benefits from irrigation, but with a changing climate and uncertainty in precipitation patterns, wastewaters will likely play a larger role supplementing irrigation water requirements. However, due to their relatively poor quality, wastewaters present challenges for sustained long-term use in olive production. Wastewaters include all effluents from municipalities, agricultural drainage, animal production facilities, agricultural processing and industrial processes. This review focuses on potential opportunities and limitations of sustaining olive oil production in the Mediterranean region using wastewater of various sources. The primary challenges for using such wastewaters include concerns related to salinity, sodicity, metals and trace elements, nutrients, organics, and pathogens. Organics and plant nutrients in the effluents are typically beneficial but depend on dosages.

Many studies have shown that saline wastewaters have been successfully used to irrigate olives in Greece, Israel, Italy, Jordan and Tunisia. Still, olive varieties and rootstocks have different tolerances to salinity and could respond differently and oil quality may improve or be compromised. Salts and trace elements need to be monitored in plants and soil to make sure accumulation does not continue from year to year and that soil physical conditions are not affected. Some food industries generate effluents with suitable characteristics for irrigation but one must balance the benefits (e.g. addition of nutrients), detriments (e.g. addition of salts or other limiting chemicals) and costs when determining the feasibility and practicality of reuse. Long-term accumulation of trace elements and metals will likely limit the feasibility of using industrial-originating effluents without treatment processes that would remove the toxic constituents prior to reuse. Therefore, untreated wastewaters from the many industries have limited long-term potential for reuse at this time. Application of olive mill wastewater may be agronomically and economically beneficial, particularly as a local disposal solution, but there are concerns associated with high-concentrations of polyphenols that may be phytotoxic and toxic to soil microbial populations.

With regards to human safety, risk of contamination of table olives and olive oil is very low because irrigation methods deliver water below the canopy, fruits are not picked from the ground, processing itself eliminates pathogens and the irrigation season typically ends days or weeks before the harvest (depending on the climate condition). Finally, considering physiological, nutritional and intrinsic characteristics of this species, it is clear that olive trees are appropriate candidates for the reuse of recycled water as an irrigation source.

1. Introduction

Olive trees are a cultural and historical icon in the Mediterranean landscape. The cultivation of olive trees dates back thousands of years to the early Bronze Age and olives are frequently mentioned in Greek mythology (Connor, 2005; Liphschitz et al., 1991; Loumou and Giourga, 2013). Today, orchards in Spain, Italy, Greece, and Tunisia produce the vast majority of the world's olive oil supply. With the increased popularity in the use of olive oil for cooking and consumption, the global demand for this healthy oil continues to grow. And with this increase in popularity, olive oil production has, in recent times, expanded far beyond the Mediterranean region to California (UC Olive Center, 2018) and many countries in the southern hemisphere including Australia, Argentina, Peru, and Chile (Torres et al., 2017).

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[*] Corresponding author.
E-mail address: fpedrero@cebas.csic.es (F. Pedrero).

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While olive orchards have thrived for centuries on rain alone (Connor and Fereres, 2005), olive oil production has become more dependent on irrigation, which has shown to improve oil production while sustaining quality (Dag et al., 2014; Orgaz and Fereres, 2004). However, in the Mediterranean region, like other semi-arid climates, water is scarce and climate change is expected to exacerbate water scarcity by adding uncertainty to precipitation patterns, producing more frequent and severe droughts and reducing the overall rainfall in the region (IPPC, 2013). With the uncertainty and likely future reduction of precipitation in the Mediterranean area, supplemental water supplies become not only attractive but a necessary option for the region to sustain its historical importance in olive oil production.

The likely source of the needed supplemental water for olive irrigation is recycled wastewater, much of which currently goes unused. Groundwater in the Mediterranean region is already over depleted, so a sustained increase in groundwater extraction from wells is unlikely, particularly in coastal areas experiencing salinization from seawater intrusion (Pedrero et al., 2018). There are many opportunities to utilize wastewaters from various sources such as treated wastewater from municipalities and wastewaters from agricultural production (e.g. olive mills, canneries, vineyards, food processing plants, drainage waters, etc.). Wastewaters, however, are typically poorer in quality than the water used to produce the waste. This poor-quality water can present challenges for sustained long-term use in olive production. Particularly problematic are industrial wastewaters from textile processing and oil production that have elevated heavy metal concentrations and/or organic fractions that pose health risks.

This review will address the potential opportunities and limitations of sustaining olive oil production in the Mediterranean region using wastewater of various sources. The review is divided into sections with specific categories identifying sources and their qualities that can either limit or enhance utilization of the water.

2. Studies using recycled wastewater for irrigation

By definition, wastewaters are any waters that have been adversely affected in quality as a result of anthropogenic influence. Such wastewaters can come from agricultural, municipal, and industrial activities. Many studies have been conducted over the years on the reuse of various wastewaters for irrigation (Asano et al., 2007; Jiménez and Asano, 2008; Pescod, 1992; Rhoades et al., 1992; Levy et al., 2011).

2.1. Recycled (reclaimed) municipal wastewater

The use of reclaimed municipal water (RMW) in agriculture is a growing practice in areas with limited freshwater resources (Pedrero et al., 2010). Within the past decade, scientific articles have been written that focus on the use of treated wastewater to irrigate various tree and vine crops including grapefruits (*Citrus paradisi*) (Pereira et al., 2011), lemons (*Citrus limon*) (Pedrero and Alarcon, 2009), mandarins (*Citrus clementina*) (Pedrero et al., 2013), nectarines (*Prunus persica*) (Vivaldi et al., 2013, 2017; Pedrero et al., 2018), almond (Vivaldi et al., 2019), avocados (Yalin et al., 2017) and grapes (*Vitis vinifera*) (Mendoza-Espinosa et al., 2008; Weber et al., 2014). While some components of the wastewater raise concern such as salts and specific, potentially toxic ions (i.e. Cl, Na and B), these studies among others (Asano et al., 2007) have shown that recycled municipal wastewater, with proper management, could be used successfully in agricultural production systems (Pedrero et al., 2014, 2015; 2016; 2018, Romero-Trigueros et al., 2014, 2017a,b; Vivaldi et al., 2017).

Unlike most fruit and nut crops, olives are relatively tolerant to salinity (Grieve et al., 2006) so it is not surprising that many studies have shown that saline wastewaters can be successfully used to irrigate olives (Bedbabis et al., 2015; Erel et al., 2019; Romero-Trigueros et al., 2019). In Greece, treated wastewater was applied for 2 or 3 years as investigators measured oil production and quality, finding that polyphenol content increased and the percentage of fatty acids consistently decreased with increasing soil salinity (ECe) (Bourazanis et al., 2016; Petousi et al., 2015). These researchers also monitored the trees and soil for salt accumulation, trace elements, heavy metals, and potential pathogens. Two different varieties (‘Leccino’ and ‘Barnea’) of olive trees were tested using reclaimed municipal wastewater vs freshwater as irrigation sources in Israel. After four years, no effects on tree growth, fruit yield, or oil productivity were found, nor were there any significant differences in nutrient and mineral accumulation in leaves (Segal et al., 2011). After eight years of treatments, despite the benefits of added nutrients to olive trees, soil degradation became a concern in the plots irrigated with municipal wastewater due to a relative increase in sodium (Erel et al., 2019). In Italy, Palese et al. (2009) examined the effect of irrigation with treated wastewater on the microbiological composition and quality of both soil and olive fruit. In Jordan, Batarseh et al. (2011) and Ayoub et al. (2016) investigated the impact of reclaimed water use on soil properties and heavy metals and on the translocation of essential nutrients to olive leaves and fruit quality parameters. They found that irrigation with mildly saline wastewater (ECw 0.8–2.7 dS/m), did not affect fruit quality parameters. In Tunisia, field experiments were conducted to investigate the effects of treated wastewater on olive growth yield, oil quality and concentration of nutrients, trace elements and minerals on olive leaves and soils (‘Chemlali’ variety) (Bedbabis et al., 2009, 2010; Benincasa et al., 2012; Ben Rouina et al., 2011; Tekaya et al., 2016). These studies not only demonstrated that such wastewater could be used to irrigate olives, but that the use brought about plant nutritional benefits as well. The investigators, however, cautioned that: olive varieties have different tolerances to salinity and could respond differently; oil quality may improve or be compromised; salts and trace elements need to be monitored in plants and soil to make sure accumulation does not continue from year to year and soil physical conditions are not affected; and that potential pathogens may need to be monitored to avoid health risks.

2.2. Agro-industry wastewater

Wastewater from agricultural-industries such as cotton, canning and food processing, dairies, distilleries, and meat processing, typically have medium to high potential for use for irrigation (Lens, 2002). The food industry comprises many different types of sub-industries and is recognized by its high-water consumption per ton of product (Casani et al., 2005). Another relevant characteristic is the importance of maintaining clean and hygienic conditions during all processes (Liu and Haynes, 2011). Therefore, cleaning and sanitizing compounds are often found in their wastewater effluents, some of which may affect the reuse potential (Levy et al., 2011). Agricultural-industry wastewater is often seasonally available and characterized by high volumes and high organic contents (Cervantes et al., 2006).

The food processing industry is the second-largest consumer of water worldwide, after agriculture (Hoekstra and Chapagain, 2007) and consequently generates large quantities of wastewater, presenting a large, often untapped, potential for wastewater reuse (Mohsen and Jaber, 2003). Against the common belief that wastewater from the agricultural industry is detrimental to the environment and therefore unsuitable for reuse, it has been shown that some food industries generate effluents with suitable characteristics for irrigation (Hien et al., 1999; Oliveira et al., 2009; Libutti et al., 2018). Some examples of these industries are wastewaters from canneries, packing houses, cheese factories, olive mills and wineries. The composition and concentration of constituents such as nutrients, salts and organic matter can vary widely among food processing operations. For example, winery and olive mill effluents typically contain considerably higher concentrations of K^+ compared to municipal wastewater sources. Additionally, effluents from all food processing operations contain considerable amounts of organics, particularly those from cheese factories that can cause nuisance due to high BOD if not pre-treated in holding basins.

Fruit and vegetable canning industries generate wastewater with high potential for reuse, but sanitation practices during processing can affect effluent quality. While cooling, heating and sterilization activities together with the processing of raw products generate effluents with up to 60 mg/l N and 22 mg/l P, a substantial amount of salt can be added to the effluent from cleaning and chemical peeling processes (CTC, 2008). For example, an ECw over 7 dS/m has been observed in some effluents, requiring reverse osmosis to decrease salinity prior to reuse (CTC, 2008). Therefore, one must balance the benefits (e.g. addition of nutrients), detriments (e.g. addition of salts or other limiting chemicals), and costs when determining the feasibility and practicality of reuse.

2.3. Agricultural drainage waters

In many arid parts of the world such as Australia, the Middle East, the Soviet Union and the United States, large quantities of saline drainage waters exist that are often considered to have little value for irrigation. However, depending upon their availability and quality, such water may be suitable for irrigation, particularly of crops with higher salt tolerance (Grattan et al., 2014). Examples of successful use of agricultural drainage water include Australia, Egypt, India, Israel, Jordan, Mediterranean countries, Tunisia and the United States (Rhoades et al., 1992). Salinity, sodicity, specific ions, and trace elements all affect the water's suitability. But proper management is necessary to avoid salinization, accumulation of specific constituents in the soil, and maintenance of good soil structure (Oster and Grattan., 2002). The method of application can vary, such as blending sources of water to achieve a suitable quality, or by applying the wastewater over space (e.g. sequential reuse) or time (e.g. cyclic reuse) to allow for crops of various tolerances to salinity (Grattan et al., 2014). For more information on drainage water reuse management practices and strategies see books and reviews by Grattan et al., 2014; Oster and Grattan, 2002; Rhoades et al., 1992; Tanji and Kielen, 2002; Wallender and Tanji, 2012.

2.4. Textile wastewaters

Effluents from the textile industry have also been explored as a potential supplemental sources of irrigation water. However, the presence of commonly used synthetic dyes can have dire consequences on the environment. Untreated effluents can contain, among other constituents, naphthol, acetic acid, soaps, auxiliary chemicals and heavy metals such as Cu, As, Pb, Cd, Hg, Ni and Co which are toxic (Kant, 2012). Moreover, some effluents, when applied to soil, can reduce infiltration due to the presence of colloidal and oily material. Despite these concerns, investigators from Jordan found that textile wastewater was suitable for irrigation of olive despite small yet significant increases in leaf N, Na, Cu, Fe, Mn and Pb concentrations (Al-Absi, 2008). Nevertheless, long-term accumulation of trace elements and metals will likely limit the feasibility of using this effluent without treatment processes that would remove the toxic constituents prior to reuse. Therefore, wastewaters from the textile industry seem to have limited long-term potential for reuse at this time.

2.5. Produced water from oil and gas fields

Petroleum and gas extraction processes produce a considerable amount of wastewater. This ‘produced’ water (PW) is typically very saline due to interaction with geologic hydrocarbons during extraction. Treatment and disposal of this brine is costly for the oil industry and the wastewater can cause environmental problems or damage neighboring agricultural fields. While PW from shale gas, conventional natural gas, and conventional oil fields typically are very poor in quality (i.e. with chloride concentration > 30,000 mg/L), about 25 % of PW, particularly from coal bed methane operations, are less saline (i.e. < 5000 mg/L) (B. Alley et al., 2011; Bethany Alley et al., 2011). Nevertheless, most of the PW contains metals and metalloids that are unsuitable for irrigation, and the presence of certain organic petrochemicals may also be a concern. Treatment, dilution, and reuse for irrigation have been proposed as an option, despite the fact that PW contains salts, sodicity and metalloids above levels considered suitable for irrigation (Echchelh et al., 2019). Such a practice has operated in Bakersfield, California, an arid region where agriculture and oil production co-exist, for the past 30 years (Waterboards of California, 2019). Although verification of health concerns has yet to be verified, an expert panel is currently examining the long-term suitability and feasibility of such reuse practice. Moreover, because the salinity and sodicity of this water is often at or above seawater levels, one must consider whether this water actually could increase the overall ‘useable’ water supply if it were blended with fresh water (Grattan et al., 2014), or if extensive treatment could make this water economically feasible (Echchelh et al., 2019).

2.6. Olive mill wastewater

Wastewaters from the olive industry have also been considered for irrigation. Murillo et al. (2000) investigated the feasibility of using wastewater from the table-olive industry to drip irrigate an olive orchard in Spain. The investigators tested two wastewaters (ECw 3.5–4.2 dS/m and SAR 12-56) and (ECw 4.3-6.0 dS/m and SAR 73-90) and found that they adversely affected the water relations and photosynthesis rates in trees compared to those irrigated with conventional water (ECw 1 dS/m), just two weeks after imposing the treatments. While the quality of the effluent was variable, SAR values reached levels that affected soil structural stability. The investigators concluded that this type of wastewater was unsuitable for irrigation, even though there was no attempt by investigators to reduce the SAR of the effluent via gypsum or other amendments.

Others have looked at the use of olive mill wastewater (OMWW) for irrigation and have concluded that such waters present both opportunities and challenges (Al-Absi, 2009; Mechri et al., 2011; Bedbabis et al., 2010, 2014). The discharge of OMWW is a major environmental challenge that affects olive-oil producing countries (Paredes et al., 1999; Obied et al., 2005). For example, in the Mediterranean countries, more than 30 million m^3 of OMWs are produced during the harvest and olive-press season (approximately 2–3 months in each olive-tree production area). Like urban wastewaters (Barbera et al., 2009), the use of OMWW (Roig et al., 2006) is potentially useful not only as a supplemental source of water, but also as a source of organic matter, typically deficient in Mediterranian soils (Moraetis et al., 2011), and as bio-based pesticides against weeds, fungi and nematodes (Cayuela et al., 2008). Even though spreading OMW is potentially environmentally and economically beneficial, there are concerns associated with high concentrations of polyphenols that may be phytotoxic to crops and toxic to soil microbial populations (Barbera et al., 2013; Buchmann et al., 2015). Moreover, these waters can cause soil hydrophobicity (Peikert et al., 2015) and deteriorate soil structure due to high K (Levy et al., 2018). Nevertheless, the polyphenols, depending upon the environmental conditions, can be readily degraded, particularly if applied during the spring rather than late fall or winter (Barbera et al., 2013; Buchmann et al., 2015). In a study comparing different rates of OMWW, investigators found that 100 m^3/ha/year was optimal in terms of olive oil quality and composition, and that higher and lower rates were suboptimal (Brahim et al., 2016). Nevertheless, some studies reported that spreading OMWWs at modest rates did not impact yield (Galoppini et al., 1992; Zipori et al., 2018), and did not cause phytotoxicity or deteriorate soil physical and hydraulic properties (Levy et al., 2018). However, at higher doses ($> 800\ m^3\ ha^{-1}$), phytotoxic effects occurred resulting in tree mortality the second year of application (Gioffré et al., 2004) and the spreading of OMWW induced a shift in the soil fauna community (Kurtz et al., 2015). Due to the small volumes, seasonality and tendency to spread the OMWW on the surface between tree rows, the nutritional benefits (N, P, K) from its application, while recognized, are expected to be small in terms of overall orchard requirements (Steinmetz et al., 2015).

3. Feasibility of using wastewaters for irrigation

The feasibility and limitations of using any wastewater for irrigation depend not only on its abundance and availability but also on its overall quality. Some wastewaters are produced only at certain times of the year, such as wastewaters from agricultural production (i.e. olive oil wastewater, cannery wastewater, vineyard wastewater, and drainage waters). In contrast, others have a steady supply (i.e. treated municipal wastewater). In most cases, wastewater will only supplement existing water supplies and the disconnect between wastewater production and orchard demand will likely require water storage facilities. While the question of wastewater supply and availability are certainly important, the focus of this review is on the quality of the wastewater and how various water quality parameters could potentially affect the soil, the tree, and the oil produced.

The quality of wastewater can limit the feasibility of its reuse for olive oil production. Some constituents in the water can be beneficial, such as nutrients and organics, while others can be detrimental, such as salts, sodicity, trace elements, and pathogens. The composition of the water, particularly the cation ratios, can affect soil aggregate stability, which in turn affects soil physical conditions and water infiltration. The major types of water quality constituents in relation to the type of wastewater are provided in Table 1 where their potential benefits or detriments for irrigation are rated as high, moderate, or low.

3.1. Salinity

The quality of the wastewater can have a profound impact on olive oil production. All irrigation water, particularly wastewaters, contains dissolved mineral salts, but the concentration and composition of the dissolved salts will vary depending upon the water source, and on treatment and storage methods. Too much salt can reduce tree growth and production, and particular constituents in the water (i.e. chloride, boron and sodium) can damage the tree via injury from specific ion toxicity, reduce flowering and affect fruit development (Grieve et al., 2006).

Salt stress via osmotic effects and specific ion toxicities can collectively work together damaging the tree (Läuchli and Grattan, 2012). Investigators have found olive to be unaffected at soil salinities, measured as saturated paste extract electrical conductivity (ECe), of 3 – 6 dS/m (Aragüés et al., 2005), which is consistent with its moderately tolerant ranking. As time under exposure to salts increases, however, tolerance may decline due to progressive toxic levels of salts accumulated in leaves or woody tissues. For example, two years after planting and imposition of salt stress, the olive cultivar ‘Arbequina’ was rated as salt tolerant with a threshold (EC_e) of 6.7 dS/m. A year later, the threshold decreased to 4.7 dS/m. By the fourth year of the study, Arbequina was rated as moderately salt-sensitive as the threshold declined to 3.0 dS/m (Aragüés et al., 2005). In a long-term field experiment (i.e. 8 years) on mature olives (cv ‘Picual’), supplemental irrigation with salinity up to 10 dS/m (combined sodium and calcium chloride) did not adversely affect tree growth, fruit yield or fruit size but irrigation management practices (low amount of applied water) and winter leaching from rainfall maintained the upper 30 cm of soil low in salinity (Melgar et al., 2009).

In a lysimeter study on young fruit-producing "Barnea" olive trees, Ben-Gal et al. (2017) controlled both irrigation water salinity and the leaching fraction. The resulting nine levels of root zone salinity provided response functions with decreased yield beginning from the lowest salinity levels and no sign of threshold value, and no distinction in response due to cause of salinity. The response was well represented by a sigmoidal declining curve with 50 % yield reduction corresponding to EC_e of 4.2 dS/m. The mechanisms for salinity tolerance/response were mainly credited to osmotic responses and restricted transport of toxic ions to aerial tissues, coming at a high cost actualized as restricted

Table 1
Risk assessment table of different types of waste waters for irrigation of olives.

	Valuable nutrients			Salinity		Phytotoxic elements			Other compounds
TYPES OF WASTE WATERS	**N**	**P**	**K**	**ECw**	**SAR**	**Cl**	**Na**	**B**	**Heavy metals and/ or organic components**
[1]Recycled municipal wastewater	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨
[2]Agro-industry wastewaster	🟩	🟩	🟨	🟥	🟨	🟨	🟨	🟨	🟥
[3]Agricultural drainage waters	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟨
[4]Textile wastewaters	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟥
[5]Produced water from oil and gas fields	🟨	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥
[6]Olive mill wastewater	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟩	🟥

Low	Moderate	High
🟩	🟨	🟥

*Risk levels is site specific and may also change according with types of water treatments.

1 - Palese et al., 2006; Bedbabis et al., 2009, 2010; Ben Rouina et al., 2011; Batarseh et al., 2011; Benincasa et al., 2012; Bedbabis et al., 2015; Petousi et al., 2015; Bourazanis et al., 2016; Ayoub et al., 2016; Tekaya et al., 2016; Erel et al., 2019; Romero-Trigueros et al., 2019.

2 - Hien et al., 1999; Cervantes et al., 2006; CTC, 2008; Oliveira et al., 2009; Levy et al., 2011; Libutti et al., 2018.

3 - Rhoades et al., 1992; Oster and Grattan., 2002; Tanji and Kielen, 2002; Wallender and Tanji, 2012; Grattan et al., 2014.

4 - Al-Absi, 2008; Kant, 2012.

5 - B. Alley et al., 2011; Bethany Alley et al., 2011; Grattan et al., 2014; Echchelh et al., 2019.

6 - Murillo et al., 2000; Gioffré et al., 2004; Roig et al., 2006; Al-Absi et al., 2009; Bedbabis et al., 2010, 2014; Mechri et al., 2011; Moraetis et al., 2011; Barbera et al., 2013; Buchmann et al., 2015; Brahim et al., 2016; Kurtz et al., 2015.

root growth and increased root mortality (Ben-Gal et al., 2017; Soda et al., 2016). This comprehensive study suggests that olive is more sensitive to salinity that what has been reported in the literature. Similar observations have been found with pistachio grown in lysimeters (Ferguson et al., 2002) as opposed to those grown in field conditions suggesting that the extensive root systems of these trees (olives and pistachios) may be extracting water from pockets of low saline environments in the field giving them a false tolerance to salinity.

Erel et al. (2019) recently demonstrated from a long-term study that, even though soil salinity was higher in treatments irrigated with RMW compared to freshwater, this did not lead to increased leaf Na or Cl concentrations or to reduced tree productivity. These results are likely influenced by the environmental conditions at the study site that included winter rainfall sufficient to leach the salts accumulated before each irrigation season.

Even though classified as moderately tolerant (Grieve et al., 2006), high salinity has been demonstrated to be detrimental to olive tree health and production (Chartzoulakis, 2005; Ben-Gal et al., 2017). Much of olive's tolerance to salinity is dependent upon the rootstock and its ability to exclude Na and Cl from being transported to the scion where they can accumulate in leaves to injurious levels (Chartzoulakis, 2005; Soda et al., 2016). Since most olive trees are grown on their own roots, the level of tolerance is cultivar dependent. Cultivars that are more sensitive to salinity absorb substantial amounts of Na$^+$ and Cl$^-$ from the soil solution and transport it to the shoot (Fig. 1). For example, cultivars 'Amphissis' and 'Agouromanaki' accumulate more Na$^+$ in their leaves than do 'Kalamata' and 'Kerkiras' and are more sensitive to Na$^+$ toxicity. Note also that while roots typically contain higher concentrations than their corresponding leaves, the ratio of leaf Na/root Na can vary dramatically. In the study by Chartzoulakis (2005), the ratio varies from 30 to 98 %. In Israel, Barnea, a variety considered particularly tolerant to salt, was found to have ten times more Na$^+$ and 5 times more Cl$^-$ in roots compared to leaves after three years of salinity treatments (Ben-Gal et al., 2017; Soda et al., 2016). In other studies, investigators also found that salt tolerance differences in olive cultivars are related to salt transport restrictions and found that most to least tolerant cultivars were 'Chemlali' > 'Chetoui' > 'Arbosana I43' > ' Koroneiki' > "Arbequina I18' (Kchaou et al., 2010) based on retention of Na and Cl in the roots.

3.2. Boron

Boron can be found in wastewaters in places where B laden detergents are used or where the original water source contains B. Some groundwater is high in B and reverse osmosis desalination of seawater retains B at relatively high levels (Yermiyahu et al., 2007). Since B becomes toxic to plants at relatively low levels, in Israel, where all wastewater is treated and used for irrigation, the use of B in detergents has been prohibited through legislation, and desalination plants providing municipal water are required to use post-treatment methodologies to remove the B. Boron supplied with irrigation water absorbs strongly onto soil clay and organic component surfaces and is difficult to leach. Soils previously irrigated with high B water can provide toxic conditions for crops for many years, even after the addition of B-laden irrigation water has ceased (Yermiyahu and Ben-Gal, 2017). While for olives B deficiency is more commonly handled in the literature than B toxicity, olives are understood to be "somewhat tolerant" to B (Benlloch et al., 1991). This tolerance level is in spite of, similar to salinity in general, large differences reported between cultivars. Olives irrigated with water containing B at concentrations as low as 0.5 mg/L have been found to have decreased photosynthesis, growth, and yield (Rostami et al., 2017; Chatzissavvidis and Therios, 2010).

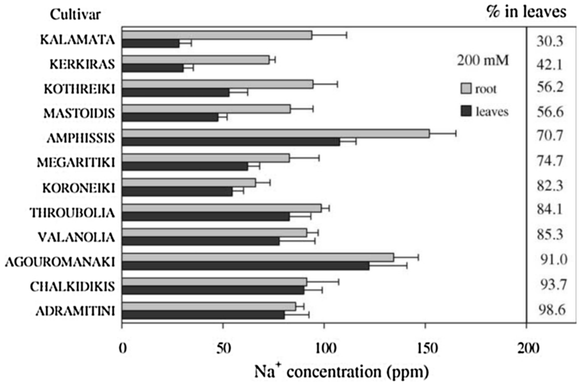

Fig. 1. Concentration (mg/kg dry wt.) of Na in roots and leaves of 12 olive cultivars grown for 5 months in 200 mM NaCl (from Chartzoulakis, 2005) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.3. Influence on oil quality

Olive trees are commonly irrigated with marginal or low-quality water in different countries (Petousi et al., 2015). The irrigation water quality, especially salinity, affects both fruit and oil quality parameters. In order to understand which are the effects of brackish recycled water on oil quality, we have to understand first how saline water and the level of salinity in the soil (EC_e) affect olive oil quality and then evaluate if and how more nutrients in the water could mitigate the effect of saline water. As suggested by Tietel et al., 2019, several quality parameters are consistently and significantly affected by soil salinity. In particular, polyphenol content increases and the percentage of 16:1 and 18:3 fatty acids and ratio of 18:2/18:3 consistently decreases with increasing exposure to salinity. Moreover, the amount of 16:1 and 18:3 fatty acids show high variability in response to brackish water irrigation (Romero-Trigueros et al., 2019; Tekaya et al., 2016; Bourazanis et al., 2016; Ben Ahmed et al., 2009; Ben Brahim et al., 2016; Stefanoudaki et al., 2009) probably because other compounds in the water mitigate or negate their effects (Tietel et al., 2019). The variability could be exacerbated if we consider that irrigation with saline wastewater (EC 4.6–6.5 dS m^{-1}) has shown faster ripening and higher contents of chlorophyll, carotenes, oxidative stability and fatty acid composition than those irrigated with low salinity water (Bedbabis et al., 2010, 2014; Benincasa et al., 2011; Gharsallaoui et al., 2011). However, one study found the opposite where the carotene and polyphenol content decreased due to irrigation with saline wastewater (Benincasa et al., 2011). Investigators also found that the water content of olives significantly increased while the fruit oil content was not influenced (Bedbabis et al., 2015). Still, others found that irrigation with mildly saline wastewater (EC 0.8–2.7 dS/m), did not affect fruit quality parameters (Ayoub et al., 2016; Palese et al., 2006). This was the case as well even after long-term (8 years) irrigation with relatively salty (1.7 ± 0.2 dS/m) water on the cultivars `Barnea´ and `Leccino´ (Basheer et al., 2019). Ahmed et al. (2009) compared field-grown olives trees irrigated with an EC of 1.2 and 7.5 dS/m. They found that major phenolic compounds (tyrosol, hydroxytyrosol, vanillic acid) and total phenol concentrations in virgin olive oil increased under saline irrigation as compared to those irrigated with non-saline water. Also, virgin olive oil from saline treated plots showed higher contents of oleic, linoleic, linolenic and heptadecanoic acids than those irrigated with fresh water. Nevertheless, oils from both treatments were classified as 'extra virgin' olive oil. Finally, the application of water stress as regulated deficit irrigation (RDI) and the combination of both stresses (saline reclaimed water and RDI) have been recently investigated (Romero-Trigueros et al., 2019). A 2-year experiment was conducted, and results indicate that that the application of saline reclaimed water significantly reduced oil yield (a 25 % reduction). The combined application with RDI increased acidity levels in olive paste as compared to that from full-irrigation treatments; however, it reduced oil extractability and yield.

The finding about oil quality indicated that olive exposure to saline reclaimed water, regardless of the water amount, decreased oil quality mainly due to the reduction of oleic acid and the increase of C18:2/C18:3 ratio and peroxides. On the contrary, the combination between saline reclaimed water and RDI improved the total polyphenols. Therefore, with appropriate management, saline reclaimed water and RDI strategies have considerable potential but long-term studies using these management techniques should be investigated to ensure that such a practice can sustain oil yields and quality.

For all the reasons reported above, it is still unclear which is the driving force of brackish recycled water that influence oil quality. Is it osmotic stress from the salts or the effect of added minerals themselves or components accumulated by the trees as osmoregulators that affect the quality parameters?

3.4. Impacts on soil physical conditions

Sodicity has been described in different ways (Jurinak and Suarez, 1990). The sodicity of soil is characterized by the exchangeable sodium percentage (ESP), the relative amount of the cation exchange capacity occupied by sodium. The sodicity of the water, on the other hand, is a measure of the sodium adsorption ratio (SAR). SAR has been the standard for predicting the potential permeability hazard an irrigation water of a given quality would have on soil structure (Ayers and Westcot, 1985; US Salinity Laboratory Staff, 1954). SAR is defined as

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})}}$$

where the concentrations are molarities. The Ca^{2+} + Mg^{2+} concentration would need to be divided by 2 if units are expressed in meq/L or mmolc/L $SAR = Na^+/\sqrt{(Ca^{2+} + Mg^{2+})/2}$ (Jiménez and Asano, 2008). The ESP and SAR are related to one another and for most practical purposes are numerically equivalent in the range of 3–30 (US Salinity Laboratory Staff, 1954).

At the soil surface, infiltration rates and soil structure can be adversely affected by salinity and sodicity, particularly when irrigation with non-saline water or rain follows irrigation with saline-sodic water. Water infiltration rates (Oster and Schroer, 1979) and the soil hydraulic conductivity (McNeal and Coleman, 1966) decrease with decreasing soil salinity and with increasing exchangeable Na, or sodicity. This occurs due to the combination of clay swelling and instability of soil aggregates (Quirk, 1978). The EC vs SAR relationship (Fig. 2) illustrates zones where combinations would likely cause a 'severe reduction in infiltration', a 'slight to moderate reduction in infiltration', or 'no reduction in infiltration" (Hanson et al., 2006). In reference to Fig. 2, if a wastewater with an ECw of 1.0 dS/m and SAR of 2 was used for irrigation, this water would likely pose little hazard to water infiltration. If, on the other hand, a wastewater with and ECw of 1.0 dS/m had an SAR of 20, it would likely pose an infiltration hazard.

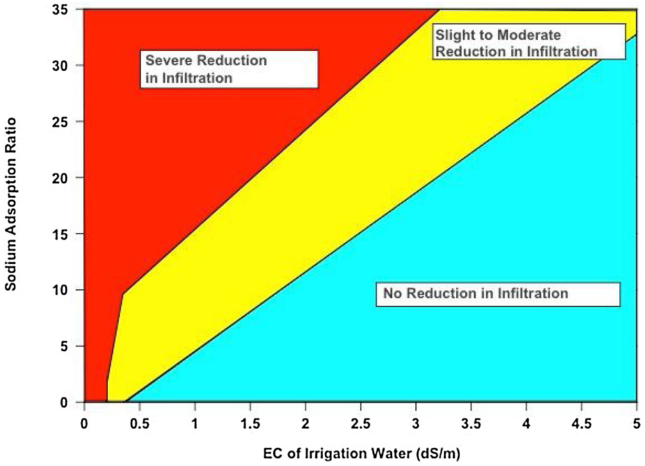

Fig. 2. Relationship between the salinity (EC) and sodicity (SAR) of the waste water and its potential effects on soil water infiltration (Adapted from Hanson et al., 2006).

Physical and chemical properties, particularly of high clay soils, have been found to be degraded following long-term irrigation with RMW (Levy and Assouline, 2011; Assouline and Narkis., 2011; Assouline et al., 2016). This occurs when the ESP in RMW-irrigated soils is greater than the SAR of the soil solution (Assouline et al., 2016; Levy et al., 2014), due to lack of equilibrium between the SAR of the irrigation water, the SAR of the soil solution, and the soil ESP.

An important component of RMW is its organic matter. Organic matter can be either a bonding or a dispersing agent, depending on the level of the ESP, the specific chemical properties of the organic matter constituents, and the degree of mechanical disturbance of the soil (Churchman et al., 1993; Nelson and Oades., 1998; Tarchitzky et al., 1999).

Potassium can be relatively and considerably high in many food industry wastewaters. For example, winery wastewater is rich in potassium (K^+) and sodium (Na^+) salts because of naturally occurring K^+ in grapes and Na^+ introduced in cleaning agents (Buelow et al., 2015). When applied via irrigation, dissolved K^+ and Na^+ can negatively affect soil chemistry and physical structure and can reduce hydraulic conductivity (Oster et al., 2016). Although K^+ is less detrimental to soil structure than Na^+ because of its smaller hydrated radius, researchers have recently found that wastewaters high in K^+ can reduce the hydraulic conductivity in vermiculite and kaolinite rich soils (Buelow et al., 2015).

Recent research has shown that while cations influence soil structural stability, monovalent (i.e. Na^+ and K^+) and divalent (i.e. Ca^{2+} and Mg^{2+}) cations are not equal to one another (Rengasamy and Marchuk, 2011; Sposito et al., 2016). For example, K^+ does not have the same dispersive power as Na^+ and Mg^{2+} and does not have the same flocculation power as Ca^{2+}. This is an important re-characterization of the impact of water quality composition on soil physical conditions as wastewater compositions can vary quite drastically from one source to the next. It has been suggested that SAR be replaced with CROSS*f* (Cation Ratio of Soil-structural Stability) as a preferred parameter to characterize aggregate stability (Rengasamy and Marchuk, 2011; Sposito et al., 2016). Using the different flocculating powers for the various cations ($Na^+ = 1.0$, $K^+ = 1.8$, $Mg^{2+} = 27$ and $Ca^{2+} = 45$), coefficients could be applied to the SAR expression. For example, the flocculating power of K^+ relative to Na^+ was $1.0/1.8 = 0.56$ and flocculating power of Mg^{2+} relative to Ca^{2+} was $27/45 = 0.60$. These investigators concluded that this $CROSS_f$ expression was much better than SAR as a predictive measure of clay dispersion and flocculation. Rengasamy and Marchuk (2011) proposed the following relationship;

$$CROSSf = \frac{Na + 0.56K}{\sqrt{(Ca + 0.60Mg)}}$$

This CROSS*f* expression has since been refined by others to optimize the coefficients for practical application. Investigators have modified the coefficients for K^+ and Mg^{2+} by equating CROSS as the weighted sum of SAR and PAR (potassium adsorption ratio). Their goal was to replace the SAR parameter with this new $CROSS_{opt}$ parameter, which was found to better predict soil stability and permeability over a wide range of wastewater compositions (Oster et. al., 2016; Smith et al., 2015; Sposito et al., 2016). While this expression is valuable regardless of water quality, it was introduced to provide more confidence in potential soil structural problems when using wastewaters that contained considerable quantities of K^+ and Mg^{2+}. The $CROSS_{opt}$ expression below is a modification of the SAR expression to include coefficients that were optimal using the soils tested by Smith et al. (2015).

$$CROSSopt = \frac{Na + 0.335K}{\sqrt{(Ca + 0.0758Mg)}}$$

Note that K^+ is added to the numerator where it has about an additional 1/3 of the dispersive effects as Na^+. Similarly, the flocculating power of Mg^{2+} is diminished by over an order of magnitude relative to Ca^{2+}. The result is that CROSS > SAR and is therefore a more conservative predictor of the effect of wastewater irrigation water on soil structure and the subsequent impact on infiltration. Use of this CROSS*opt* to replace the SAR term in Fig. 2, will likely improve the prediction of infiltration hazard of wastewaters regardless of the water composition.

Typical RMW used for irrigation in Israel has SAR > 4 (Levy et al., 2011). Eight years of deficit irrigation of olives with RMW with EC of ~1.7 dS/m, Na of ~200 mg/L and SAR of ~5 $(mmol/L)^{0.5}$ showed seasonal increase in soil EC during summer irrigation periods which was eliminated each year by winter rain leaching but steady increase in SAR resulting in high (14 %) ESP (Erel et al., 2019). Exchangeable sodium over 4% is understood to represent soils with sodic-type behavior and ESP of ~6 was suggested as the cause for diminished oxygen availability to roots in avocado grown in clay soil (Yalin et al., 2017) following irrigation with RMW. In olives, ESP of 20 % has been suggested as a threshold for impaired tree function and development (Freeman and Carlson, 1994).

3.5. Nutrients in recycled wastewater

Technological developments in the late twentieth century focused on nutrient removal (N and P) to minimize eutrophication of receiving bodies of water and to reduce the overall environmental impacts of wastewaters. But by reusing wastewater for irrigation, dual benefits of waste disposal and fertilizer application are realized.

Recycled wastewaters have varying degrees of nutrients that can be beneficial to olive production. Municipal wastewaters are particularly nutrient-rich. Indeed, concentrations of N, P, and K increased in olive leaves, fruits and roots irrigated with TMW (Bedbabis et al., 2010, 2014). And, according to Melgar et al. (2009), irrigation with TMW produced higher yields in olive trees than in those irrigated with conventional well water due to the nutrients (N, P and K) in the wastewater. In a study by Ashrafi et al. (2017), the investigators found that young olives in Iran benefited from irrigation with recycled water compared to those irrigated with non-wastewater due to the contribution of nutrients (primarily N) in the wastewater. In a study comparing irrigation of two olive varieties with wastewater to fertigated (nutritional elements provided via the drip irrigation system with the water) irrigation with fresh water, no differences were found in leaf N or K (provided by fertigation in freshwater treatments) while leaf P (not supplied with fertigation) was higher in wastewater irrigated trees. The differences in leaf P developed only after four years of treatments (Erel et al., 2019; Zipori et al., 2020).

The combined higher N along with higher salinity, typical to irrigation water originating as recycled wastewater, presents a paradox between nutrient, especially nitrogen, management and salinity control. Increased salt build-up and consequential leaching led to significant losses of N from the root zone and contamination of deep soils with nitrates when recycled municipal wastewater was used for irrigation in Israel (Segal et al., 2011; Erel et al., 2019). In a study under Mediterranean conditions, Libutti and Monteleone (2017) pointed out that since soil salinity control is bound to increase nitrogen leaching, operational criteria should optimize the volumes needed to reduce salinity and those necessary to protect groundwater from nitrate contamination. Typically, rootzone salinity increases throughout the season, whereas soil nitrogen decreases. Therefore, reclamation leaching (i.e. leaching at the end of the season), as opposed to maintenance leaching (i.e. applying a leaching fraction each irrigation), may be more effective at simultaneously controlling salinity and minimizing nitrate losses to the groundwater.

Winery wastewater is typically characterized by low pH of 3–4, high turbidity, and high COD values up to 25 g/L (Petruccioli et al., 2002) but at the same time has high N (up to 142 mg/L), high P (concentrations are generally in the range of 3–188 mg/L) (Bustamante et al., 2005) and high K. Therefore, nutrient-rich water of this sort could supply trees with supplemental nutrients, thereby reducing the amount of additional fertilizers. Typically, researchers that observe beneficial responses of crops to wastewater irrigation as compared to conventional irrigation water note that the soil nutritional status is sub-optimal. However, this also implies that these nutrient-rich wastewaters can be beneficial and reduce the overall fertilizer requirements.

One of the main characteristics of modern, intensively farmed olive orchards is that pressurized irrigation systems (e.g. drip) allow for a continuous and controlled application of nutrients (fertigation). However, the available knowledge regarding the physiological behavior of such orchards is rather scarce (Connor and Fereres, 2005), especially when taking into account the fundamental effects of nutrient availability under fertigation compared to traditional dryland fertilization (Bar-Yosef, 1999). In a long-term study in a super-intensive olive orchard irrigated with recycled municipal wastewater without additional fertilization, no nutrient deficit or reduction in yield was found in comparison to trees irrigated with freshwater and standard fertilization (N and K). Furthermore, irrigation with recycled water without adjusting the fertilization regime led to a substantial increase in environmental contamination with N (Segal et al., 2011; Erel et al., 2018, 2019; Zipori et al., 2020).

The relationships between olive mineral nutrition and two important physiological factors that influence olive tree productivity (i.e. flowering and fruit set), are complex and dependent on environmental factors such as water availability and winter chilling (Erel et al., 2013). Unfavorable environmental conditions (e.g. aridity and salinity) could additionally disrupt nutrient uptake and adversely affect tree growth and reproduction (Bustan et al., 2013).

When circumstances are favorable for flower induction, mineral nutrition, especially of macronutrients, of the tree is particularly important. Nitrogen tends to increase flowering intensity but not flower quality. Fruit set, and thus fruit number per tree, is often impaired by excess N (Erel et al., 2013; Haberman et al., 2019a). Unlike N, P nutrition works positively on fruit bearing. Fruit set consistently increased linearly as leaf P increased (Erel et al., 2013, 2016). Finally, potassium nutrition has a relatively low impact on olive productivity (Erel et al., 2013; Haberman et al., 2019b). Therefore, depending on the wastewater nutrient content and composition, olive fruit set could be significantly impacted.

Another important factor to consider in regards to olive mineral nutrition is alternate bearing. Developing fruit is a major sink for nutrients, and therefore extreme fruit loads are likely to disturb tree-scale mineral balance (Bustan et al., 2013). It appears that olive has developed mechanisms to regulate fruit load in accordance to P and N availability at the flowering stage. This way, the tree will avoid severe depletion during the fruit growth stage, which is characterized by very high nutrient demands (Bustan et al., 2011). It has been demonstrated that the risk of acute mineral deficiency during the biennial (alternate) cycle is low. Nevertheless, alternate bearing cycles are an important consideration to optimize N, P, and K application in olive in order to achieve more efficient production, improve product quality, and minimize adverse environmental consequences (Bustan et al., 2013).

While calcium nutrition is not typically cited as a beneficial nutrient in wastewaters, it can play a role in sodic or high SAR waters. The role of Ca^{2+} in cell membrane integrity and maintaining nutrient ion selectivity is well documented (Läuchli and Grattan, 2012). Moreover, calcium has been found to be important by reducing Na + mobility in olive trees (Ben-Gal, 2011; Zipori et al., 2015). This implies that gypsum applications could be beneficial when irrigating olives with sodic or saline-sodic wastewaters and would help reduce Na^+ transport to leaves or developing tissue. Gypsum applications might have been effective at improving the suitability of table olive industry effluent, which was reported to have very high and variable SAR values, as reported by Murillo et al. (2000) earlier in this review.

3.6. Trace elements and heavy metals

Trace elements and heavy metals can be problematic for the reuse of some wastewaters. Constituents such as As, Cd, Cu, Cr, Hg, Mo, Ni, Se, Pb and Zn can be soluble and biologically available for bio-concentration up the food chain. Typically, these constituents are introduced into effluents from chemically intensive industrial processes such as textile production, print board manufacturing, metal plating, semiconductor factories, etc. Metalloids are also high in many untreated produce waters. If concentrations of these constituents are high, they should be avoided from reuse or treated prior to application to reduce their concentration. Ideally, pre-treatment of effluents leaving the factories prior to arrival at the municipal treatment facilities may be a more effective means at reducing metal concentrations.

One study investigated the impact of irrigation with heavy metals on olive production. Mufeed et al. (2011) investigated the impact of irrigation with treated municipal wastewater on soil and olive trees. They found that heavy metal uptake by the olive trees (leaves and fruits) was not always related to the corresponding concentration in the wastewater, suggesting selective absorption processes and probably different adsorption strengths on soil surfaces. Generally, smaller quantities of heavy metals compared to essential elements accumulated in olive fruits and leaves. Higher levels of Fe, Mn, Ca, and Mg accumulated in olive fruits than in leaves. The general trend of heavy metal transfer from soil to tree was similar for both olive fruits and leaves (fruits: Cu > Zn > Mn > Fe > Ni > Pb > Cd, and leaves: Fe > Zn > Mn > Cu > Ni > Pb > Cd), suggesting a consistent preference of essential over non-essential metal transfer from soil to plant. However, there were some differences in the essential metals, with Fe preferentially accumulated in leaves while Cu preferentially accumulated in the fruit. While these were general observations, it is important to emphasize that absolute concentrations, soil type and redox conditions will affect metal availability and uptake and transport processes.

Among heavy metals, Cd plays a major role; its presence is due to the growing use of sewage sludges and other wastes in agricultural land (Al-Absi and Mohawesh, 2009). Absorbed by plants and thereby entering the food chain (Crosby, 1977), Cd presents a severe risk to human health.

3.7. Organics

Municipal wastewater influent, before it becomes a suitable water source for agriculture, must undergo a series of treatment processes to reduce the amounts of components such as chemicals, organic matter (OM) and microorganisms below specific thresholds. In particular, OM is an important component represented by two indicators; total organic carbon (TOC) and degradable organics (i.e. chemical oxygen demand COD and biological oxygen demand BOD). Investigators consider organic matter an important component of treated wastewater because it enhances soil physical and chemical properties promoting favorable conditions and improving the growth of certain crops (Hargreaves et al., 2008; Mohammad and Mazahreh, 2003; Xu et al., 2010; Nagel et al., 2003; Speir et al., 2003; Bahri, 1987). There are some studies that found medium and long-term benefits due to OM in TMW on olive orchards. For example, Bedbabis et al., 2014 demonstrated an increase in OM after 5 and 10 years in soils irrigated with treated wastewater (COD 73.0 mg/L and BOD 22.0 mg/L) compared with well water (COD 0.0 mg/L and BOD 0.0 mg/L), making this effluent not only an excellent source of carbon but an organic soil fertilizer as well.

While organic matter is able to retain nutrients necessary for plant growth and release them over time as the material is oxidized, it can immobilize metals from the wastewater due to its high adsorptive capacity (García et al., 1995). This reduces their availability for plant uptake. However, high OM in the effluent could increase the potential of emitter clogging (Keser and Buyuk, 2012; Xu et al., 2010) and stimulate re-growth of bacteria (Shatanawi, 1994). This suggests that low to moderate concentration of OM could be more useful for crops than high concentration.

Petroleum organics may also be problematic in produce water. Some may be pre-existing in the petro oil-water fraction that is extracted, and others are introduced.

3.8. Pathogens/Treatment/Irrigation methods

Typically, wastewaters from municipalities and animal production facilities that are inadequately treated pose a great threat to human health. The wastewaters, depending upon their source and level of treatment, may contain various pathogens such as bacteria, helminth eggs, fecal coliforms and viruses that could pose a health risk to humans. Over the last decade, a number of scientific studies focusing on the use of treated wastewater for irrigation of tree crops were published. These studies included consideration of fruit safety from a pathological point of view on crops such as mandarin (*Citrus clementina*) (Pedrero et al., 2013, 2016), grapefruit (*Citrus paradisi*) (Pereira et al., 2011), lemon (*Citrus limon*) (Pedrero and Alarcón, 2009), nectarine (*Prunus persica*) (Vivaldi et al., 2013, 2017), and grapevines (*Vitis vinifera*) (Mendoza-Espinosa et al., 2008). Recently, it has been demonstrated that agriculture requires careful monitoring of a range of hygiene parameters, including the presence of potential human pathogenic bacteria (HPB) (Palese et al., 2009; Becerra-Castro et al., 2015).

For olive trees, an exhaustive evaluation of the possible persistence of HPB, demonstrated that, excepting for two cases (Clostridium and Enterococcus) that should be ascertained with more sampling throughout the year and in different years, fertigation with urban treated wastewater did not cause a substantial or significant increase in the bacteria (Sofo et al., 2019).

With regards to wastewater irrigation of olive trees, three main factors are related to fruit safety. First, is whether the fruit is in contact with the irrigation water. Second, is whether the pathogens can survive the oil extraction processing method. And third, because the irrigation season typically ends days or weeks before the harvest (depending on the climate condition), whether pathogens also survive this period. Because olive trees are typically irrigated below the canopy, fruits are seldom in contact with the wastewater. And, even if the olive fruit was contaminated with a pathogen, it would have to endure the oil extraction process after the olive washing process and be subjected to olive's natural antimicrobial properties. To extract oil, the olives are first ground or milled to a paste that is slowly stirred (malaxation), making it easier to separate the water and oil phases. The paste may be pressed by spreading onto fiber plates, stacking the plates, and applying pressure to separate the liquid from the solid material. The resulting cloudy olive oil may then be allowed to separate by gravity to give a clear product. Alternatively, the paste may be centrifuged in a horizontal centrifugal separator, or decanter, to separate the oil from the solid and aqueous phases. In many producer countries (e.g. California), two-phase separation systems yielding an oil phase and wet solid phase are most common (Flynn, 2011). Sometimes the oil is filtered to eliminate solid particles remaining in the oil. These variations in production methods produce oils with different chemical and microbial characteristics. Moreover, olive oil has antimicrobial properties that have been recognized for many years. Medina et al. (2006) studied the antimicrobial activity of different edible oils and found that oils from olive fruit had strong bactericidal action against both gram-positive and gram-negative bacteria, also against foodborne pathogens on virgin olive oil and olive oil purchased from a retail market in Spain (Medina et al., 2007). Therefore, even if wastewaters used for irrigation have elevated pathogen contents, it is very unlikely that these pathogens would pose a health risk. This because 1) irrigation management would avoid fruit contamination, 2) the pathogens would have to endure the oil extraction process, and 3) the pathogens would have to survive the olive's natural antimicrobial defense mechanism. In regards to table olives, processing this fermented fruit involves brining/salting, fermentation, and/or acidification. The harsh environmental conditions found in the fermentation process (low pH, high salt content, presence of inhibitory compounds, sugar consumption, etc.), and the presence of other additional hurdles (production of bacteriocins, killer factors, addition of preservatives, etc.), make table olives an adverse habitat for the development of foodborne pathogens (Medina-Pradas and Arroyo-López, 2015). If such growth ultimately occurs, the presence of undesirable microorganisms or their metabolites is often linked to the storage or selling conditions, not to the fermentation/production process (RASFF Portal, 2012). For all the above-mentioned reasons, this widespread Mediterranean fermented fruit can be considered a safe product if good hygiene and manufacturing practices are followed and appropriated levels of salt ($> 5\%$) and pH (< 4.3) are obtained in the final products (Di Cagno et al., 2013; Heperkan, 2013).

3.9. Contaminants of emerging concern

The discussion regarding recycled wastewaters, water quality, and appropriateness for irrigation seems to be far from over. Components not previously detected, termed "contaminants of emerging concern" continue to appear in wastewater and effluent, often due to improved detection methodology (Vidal-Dorsch et al., 2012). Among the major examples of emerging contaminants in municipal wastewaters are pharmaceuticals, endocrine disrupting compounds and personal care products. Trace amounts of these are being discovered in water, particularly wastewater. Their survival rates in the irrigation-soil-crop system and possible harms of which are not yet apparent, but currently being widely studied. Textile and oil produce water often contain metalloids while other, yet to be investigated, processing or extracting chemicals may be present as well. The ultimate fate of such chemicals in the soil-plant-groundwater system needs to be investigated. In summary, emerging constituents will likely continue as wastewaters of various types and sources are considered for irrigation.

4. Conclusions

Olive is the most important tree crop species cultivated in the Mediterranean region. Olives have clear agronomic value but also play an essential role in cultural-landscape-historical composition, environment protection, and economic development. Feasibility studies of reused wastewater as a source for irrigation of olive are site-specific, dependent on pedo-climatic conditions and irrigation practices used in each specific geographical area. In the long-term, irrigation of olive with RMW increases total production per hectare, most likely due to the general positive effect of irrigation and on benefits from nutrients supplied with the water. This even though irrigation with recycled wastewater introduces salts into the soil which must eventually be leached and also in spite of the fact that nitrogen, credited for at least some of the positive effects of the RMW, can have adverse effects on both olive productivity and oil quality if given at excessive rates. The impact of recycled wastewater on oil quality is not clear due to the impossibility to generalize the effects of specific components, such as salts and nutrients, on the complex water-soil-plant system. From a microbiological point of view, the contamination risks, not only for fruits but also for farmers, are very low due to traditional harvesting practices, irrigation methods that do not wet the fruit, and an elaborate oil processing system to extract the oil. Finally, wastewater represents a strategic resource not only from a quantitative point of view for water supply but also due to its being a diluted fertilizer solution that could positively influence the production stability from the perspective of a circular economy. Other recycled water sources, including OMWW and industrial wastes, must be evaluated individually in order to consider contributions of heavy metals, phytotoxic compounds, or other contaminants restrictive to plant growth or human health. Moreover, to find an effective strategy that could spread and expand wastewater as an alternative water source, it is essential to use monitoring systems for nutrients microorganisms and toxic compounds, which would considerably reduce the risk of nutritional imbalances and therefore a production deterioration.

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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